Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BALANCING COASTAL RESILIENCE THROUGH THE COMBINED USE OF ENGINEERED AND NATURAL INFRASTRUCTURE FOR SLR PROTECTION

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ABSTRACT

Assessing the relative effectiveness of engineered (or gray) and natural (or green) infrastructure in safeguarding coastal communities from tropical cyclones, sea level rise (SLR) and associated hazards is a multifaceted endeavor that is essential for the resilience of these vulnerable regions. Engineered solutions, such as seawalls and levees, offer robust protection by creating physical barriers but may have high construction and maintenance costs and negative ecological impacts. Furthermore, they may not adapt to naturally evolving but unanticipated environmental conditions. On the other hand, green infrastructure, such as mangrove forests and marshes, provides natural defenses by absorbing and mitigating the impacts of coastal storms and SLR, which offers potential ecological benefits, and often is more cost-effective over the long term, but is not as effective for addressing immediate coastal flooding threats. Evaluating the relative effectiveness of these approaches necessitates a comprehensive analysis of factors, including specific geographic and environmental conditions, economic viability, community engagement, and ecological impact, to make risk-informed decisions that balance protection and sustainability for coastal communities facing the challenges of a changing climate.

Resilience and sustainability are distinct concepts; some strategies for enhancing resilience in the short term are sustainable while others are less so. Adaptation strategies, which by definition take place over extended periods of time, can be similarly distinguished. Green adaptations, which involve natural processes but may require decades for their benefits to be fully realized, tend to be more sustainable than gray adaptations, which involve construction of physical infrastructure to address immediate resilience problems. Identification of the correct mix of policies and adaptations to address immediate deficiencies in resilience and, at the same time, support sustainable decision-making in the long term is an essential ingredient of minimizing the impact of a changing climate on coastal communities but has received little attention in the coastal protection literature. Such policies must recognize the difference in relevant time scales of competing natural hazard demands, the deep uncertainties in current climate forecasts, public perception and tolerance of risk, and community social norms. In this presentation, we present a life-cycle analysis approach for balancing the benefits achieved by green vs gray adaptation strategies for protecting coastal infrastructure. We identify dominant contributors to risk and identify challenges in developing public policy for implementing such strategies using a moderate-sized industrial coastal community, Mobile, AL, as a testbed.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNSUPERVISED DOMAIN ADAPTATIVE SEMANTIC SEGMENTATION OF BUILDING COMPONENTS USING A SYNTHETIC IMAGE SOURCE DOMAIN.

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ABSTRACT

The semantic segmentation of building components is an important task in automating the inspections of building structures. One challenge towards building deep neural networks for this task is the development of large, annotated datasets. Unsupervised Domain Adaptation (UDA) provides one promising approach to mitigate the need for manual data. The goal of UDA is to take the features learned from a specific domain and generalize them so that they may be adapted to other, similar domains. UDA has been seen to work well in various semantic segmentation tasks such as classifying objects in photos of cities by adapting the features of synthetic city images to real city images. In this paper, we test the effectiveness of unsupervised domain adaptative semantic segmentation in classifying the components of buildings. To accomplish this, we use a dataset of synthetic building images called QuakeCity as the source domain and real images of buildings in Mexico City as the target domain. Different leading frameworks, including PiPa and DAFormer, are compared to the results of direct segmentation techniques using transformer-only DAFormer and Segformer models. Overall, both UDA models performed very similarly to one another, but both provided better results than direct segmentation alone. With further configuration and testing, UDA with a synthetic source domain could make dense classification model production more efficient, as the overhead associated with manually labeling real-world data is eliminated. Applying this to building component classification further displays these advantages, allowing the task to be more streamlined, thus improving the efficiency of building maintenance tasks altogether.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE EFFECT OF STRENGTH DISTRIBUTION AT THE MICROSCALE ON MACROSCOPIC FRACTURE STRENGTH AND ENERGY

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ABSTRACT

We study the fragmentation response of a thin ring undergoing radially expanding loading, as the analysis can be carried out in 1D and all the domain undergoes a spatially uniform and temporally increasing loading. We assume that the underlying material properties are random fields. Through adjustments to the covariance function used, various forms of material heterogeneity, e.g. length scale of variations, roughness, span of variations, can systematically be incorporated in the model. We present fragmentation response in terms of material properties (fracture strength and length scales), random field (correlation length and point-wise span) and loading rate. The main macroscopic QoIs are fracture energy loss, maximum average stress, and fragmentation size distribution. The distribution of strength at the microscale is also affected by the form of the probability density function (PDF). We adjust the form of the tail of the distribution by a shape parameter and discuss how that affects the macroscopic strength distribution for low loading rates. We also discuss the differences in the response to low and high loading rates. We present ML models that can predict key macroscopic QoIs from the scalar input parameters and a reduced space representation of the underlying random fields. Different ML-based analyses elucidate which parameters in combination with other parameters or individually affect the macroscopic QoIs the most.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MICRO-SCALE EXAMINATION OF ALTERED FRACTURE PROPERTIES IN SHALE ROCKS EXPOSED TO CO2-RICH BRINE UNDER HIGH-TEMPERATURE AND HIGH-PRESSURE CONDITIONS

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ABSTRACT

The effects of rock-reactive brine interactions on the chemo-mechanical properties of rocks can be intricate, depending on the mineral composition of the shale and brine's chemical composition. As a results of these interactions, the rock may exhibit altered mechanical and petrophysical properties. This study explores the distinctions between unreacted shale samples and those exposed to CO2 over a 28-day period at an elevated temperature of 100°C and substantial pressure of 1800 psi. A key aspect of the research involves subjecting the cross-section samples to micro-scratch testing under constant loading conditions, ensuring that penetration depth remains independent of loading forces. Mechanical assessments were based on the evaluation of brittle events, derived from the analysis of tangential force peaks, revealing a distinct transition in material behavior from ductile to brittle regions, closely tied to the dissolution and precipitation zones within the specimens. Furthermore, scratch and plowing hardness profiles were established throughout the scratch length. Scratch hardness exhibited noteworthy variations between ductile and brittle regions, influenced by distinct dissolution and precipitation characteristics. In contrast, plowing hardness offered more limited insights, particularly in the ductile region, where elevated tangential forces and higher scratch depths indicated higher material compressibility. Additionally, our research highlighted distinct variations in scratch paths between the two regions under constant loading conditions. The shale samples scrutinized in this study were obtained from carbonate-rich and silicate-rich Formations, offering valuable insights into the mechanical response of shale materials in high-temperature, high-pressure, and CO2-exposed environments.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL STUDY OF SEGMENTAL ELASTIC SPINES WITH JOINT STIFFNESS FOR BUILDINGS

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ABSTRACT

A stiff vertical structural element that runs the height of a building and is pinned at the building's base is often referred to as an elastic spine. An elastic spine can be used to prevent the formation of soft story mechanisms by imposing a pattern of approximately equal story drifts; however, large forces can develop in the spine due to higher mode effects. A proposed solution to reduce the force demand on the spine is a segmental spine. The continuous vertical spine is split into two or more separate segments in a segmental spine. Previous studies on segmental spines have shown that segmenting a spine does indeed reduce the force demand on the spine while still allowing the spine to have a beneficial impact on controlling the drift response of a structure. However, most previous work on segmental spines has been numerical, and experimental studies with segmental elastic spines are limited. Additionally, the stiffness of the joint between the segments should affect the forces developed in the spine and the pattern of allowable drifts imposed by the spine. Previous studies often treated these joints as ideal pins, neglecting the potential impact of joint stiffness on system performance. To address these gaps in knowledge, an experimental investigation of the seismic response of a structure with a segmental elastic spine was conducted. This study utilizes a five-story structure with a spine that was split into two segments. The joint between the segments was designed such that it has a moment versus rotation relationship that can be modified. This structure was subjected to a suite of ground motions using a shake table, and the resulting drifts, floor accelerations, and forces on the strongback were measured considering a range of joint stiffnesses between the segments, including nearly zero stiffness (ideal pin) and a stiffness high enough to effectively negate the segmentation. The results of this experimental study provide a quantitative, physical example of how much the forces in the segmental spine were reduced compared to the non-segmental spine and how much drifts in the structure with the segmental spine were increased. Furthermore, this study's findings demonstrate that the segmental spine joint's stiffness can be adjusted to balance drift and strongback forces.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ELASTOPLASTIC PHASE FIELD FRACTURE MODEL FOR CONCRETE IN GENERALIZED CONTINUA

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ABSTRACT

Concrete has a complex heterogeneous internal structure, because of which an involved cracking response with a gradual loss of material integrity is observed. This response is caused by the formation of cracks in a finite size fracture process zone ahead of the crack tip, in which microcracks initiate and later coalesce to form larger macroscopic ones. Due to the presence of this process zone, cracking of concrete is characterized by a material length related to its microstructure. Additionally, in real-life applications, concrete structures are under loading conditions resulting in complicated mixed-mode fracture patterns. Hence, predicting failure in concrete structures is a challenging task.

Computational fracture modeling of concrete structures, due to the high cost of experimental testing, has attracted significant attention. Among many computational techniques, the phase field approach to fracture has proven to be a well-established formulation for simulating different fracture phenomena [1]. In this approach, a crack surface is tracked implicitly through the evolution of an additional independent field that smears out the damage. However, the application of phase field formulations to complex fracturing behavior of concrete has received limited attention.

In our previous work [2], we introduced a phase field model investigating various crack driving forces considering only the elastic response of concrete. Following a thermodynamically consistent approach, we extend that model to an elastoplastic formulation which can accurately capture the quasi-brittle response of concrete, including the pressure dependency of strength. Next, to account for the internal microstructure of concrete, we extend the formulation and investigate the incorporation of the internal length scale, which characterizes the microstructure fracture response of concrete and represents the finite size of the fracture process zone ahead of the crack tip. For validation, the proposed approach is applied to different benchmark examples, and a comparison with experimental results demonstrates the model's strong performance.

References

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHALLENGES IN INTEGRATING CFD MODELING WITH UNLETB FOR GRAVEL EROSION ANALYSIS

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ABSTRACT

The University of Nebraska Lincoln Erosion Testing Bed (UNLETB) is an apparatus that evaluates the erosion characteristics of large gravels, particularly those employed in rock shoulders of highways. The device comprises a water circulation system within a large tank, generating an intense flow directed toward a gravel sample in a sample box. The applied flow subjects the gravel sample to shear stresses, inducing erosion, all while a waterproof camera records the erosion process in video format. Subsequently, the erosion profile (Erosion depth vs. Time) is extracted from the recorded video. However, analyzing the erosion profiles is not straightforward, requiring quantification to delineate the ultimate erosion depth and erosion rate. This process requires a thorough understanding of the velocity distribution within the sample box, as it governs the vectorial component of fluid-induced shear stresses on the sample. However, conventional fluid mechanics is not fully capable of accurately addressing the complicated hydrodynamics and turbulence in the sample box.

This study, therefore, resorted to computational fluid dynamics (CFD) analysis addressing turbulent flow conditions. It presents diverse trials and approaches, such as experimental velocity measurement in two directions and verifying it with the CFD model. These trials aim to overcome the complexities associated with the calibration process of the model with the hydrodynamics behavior and turbulence within the sample box.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A RIGOROUS SEMI-ANALYTICAL GRAPHICAL SOLUTION FOR UNDRAINED WELLBORE STABILITY PROBLEM IN ELASTOPLASTIC HOEK-BROWN ROCK UNDER NON-HYDROSTATIC IN SITU STRESSES

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ABSTRACT

A rigorous semi-analytical solution for evaluating the stability of an impermeable wellbore in rock formation that obeys Hoek-Brown failure criterion in a non-hydrostatic (i.e., the horizontal and vertical in situ stresses are not equal) stress field is developed in this work. The solution is expanding a previous contribution by the authors (Abu-Dayyeh et al., 2023) by overcoming the limitation of using a moderate value of the earth pressure coefficient K_0. It hence provides a complete solution for the cavity contraction problem for associated Hoek-Brown rock by covering all possible cases of K_0. The developed solution has the practical importance of effectively predicting the critical mud pressure that is essential to maintain the stability of wellbores. This solution is obtained following the recently proposed graphical method by Chen and Abousleiman (2022) which has the advantage of overcoming the singularity problem encountered in plasticity models with angular yield/potential surfaces such as Mohr-Coulomb and Hoek-Brown, and freeing the axial stress from intermediacy assumption. With the use of this method, a generalized solution for arbitrary values of K_0 is obtained, by first deriving the necessary constitutive equations for the pertaining sectors in the deviatoric plane, and then tracking the stress path as it goes through different states of stress until its final state corresponding to the (reduced) wellbore support pressure is reached. The developed equations herein are subsequently used to obtain the wellbore drilling curves for various Hoek-Brown parameters, as well as, different values of K_0. The results indeed demonstrate the capacity of this novel method to overcome the previous limitations in the literature, by showing how the intermediacy assumption for the vertical stress is not necessarily an accurate one for all the case scenarios of K_0 involved.

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATED FINITE ELEMENT NEURAL NETWORK (I-FENN) FOR VARIATIONAL THERMOELASTICITY BASED ON THE TEMPORAL CONVOLUTIONAL NETWORK (TCN)

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ABSTRACT

Multi-layer perceptron (MLP) networks have been used in various multiphysics problems, such as thermoelasticity. However, MLPs are computationally intensive and require several training instances. The Integrated Finite Element Neural Network (I-FENN) framework, which utilizes a physics-informed temporal convolutional network (PI-TCN) within a finite element method, was developed to solve these issues [1]. This work presents a new variation of I-FENN that uses a variational TCN model that minimizes the variational form of thermoelasticity, thereby offering computational efficiency and reducing memory requirements. This approach also satisfies zero Neumann boundary conditions and complies with thermodynamic principles. The results of our study show that finite element shape functions are more accurate and faster than automatic differentiation for spatial gradient calculations. The research demonstrates the framework's efficacy through various numerical examples and discusses the convergence and hyperparameter impacts of the variational TCN model. Our proposed approach offers a scalable and efficient solution for fully coupled thermoelasticity problems and can be extended to other multiphysics problems.

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Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING-BASED PREDICTION OF MECHANICAL PROPERTIES IN THERMALLY EXPOSED RECYCLED AGGREGATE CONCRETE

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ABSTRACT

Understanding how recycled aggregate concrete (RAC) performs under thermal exposure helps engineers in designing resilient structures with sustainable materials. This research project focuses on predicting the mechanical properties of RAC subjected to thermal exposure using machine learning algorithms. The integration of machine learning enhances precision in predicting mechanical properties. This research considers input parameters such as properties of normal and recycled aggregates, percentage of recycled content, additives type, additives ratio, and specific thermal exposure parameters. Specifically, this research focuses on predicting compressive strength, tensile strength, and elastic modulus in RAC specimens using two machine learning methods: decision tree and artificial neural networks. The models are trained and tested on a comprehensive dataset from prior experimental studies. Results show satisfactory accuracies with low error margins of the predictions compared to the published experimental results. This research holds practical implications for the construction industry, offering engineers and practitioners a tool to predict the RAC's mechanical performance under diverse thermal scenarios.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYBRID STRUCTURAL RESPONSE ANALYSIS FOR DAMAGE DETECTION USING RESIDUAL LSTM AND FINITE ELEMENT MODELING

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ABSTRACT

This study addresses the challenges in structural response analysis, a pivotal element in structural health monitoring and damage assessment. Traditional methods, such as experiments on actual structures or finite element models (FEM), are limited either by the impracticality of damaging real structures or by the discrepancies between model predictions and actual structural behaviors. Machine learning (ML) models, particularly those using force as an input to predict structural responses, have emerged as a promising alternative. However, training these models to accurately represent complex, real-world structures is hindered by the scarcity of suitable data, especially concerning damaged structures. To tackle these challenges, this research introduces a novel hybrid approach that combines the strengths of both physics-based and data-based techniques. The proposed method utilizes Residual LSTM models to bridge the gap between the predictive capabilities of finite element models and the actual responses of real-world structures. The innovation lies in using data exclusively from undamaged structures while also adapting the model to account for damaged scenarios. This approach eliminates the need for physical damage to structures for analysis, potentially revolutionizing the field of structural analysis and damage monitoring.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DIGITAL TWINS AND CIVIL ENGINEERING PHASES: REORIENTING ADOPTION STRATEGIES

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ABSTRACT

Digital twin (DT) technology has received immense attention over the years due to the promises it presents to various stakeholders in science and engineering. As a result, different thematic areas of DT have been explored in a bid to understand its conceptualization, implementation, and operational service. This is no different in specific fields such as manufacturing, automation, oil and gas, and civil engineering; leading to information overload with no seemingly universal directions for field-specific applications. The civil engineering industry is further disadvantaged in this regard as it relies on external techniques by other engineering fields such as manufacturing and aviation industries for its DT adoption. A rising consequence of these extensions results in a concentrated application of DT to the operations and maintenance (O&M) phase, with comparatively limited application in the planning/design and construction phases. On another spectrum, Building Information Modeling (BIM) has been pervasively utilized in the planning/design phase; further suggesting a dichotomous restriction of BIM for this phase and DT for the O&M phase. For the construction phase, while sensor-based techniques are utilized for optimized processes and monitoring, the transient nature of this phase remains a challenge for DT adoption. In this talk, we present a phase-based development of DT in the Architecture, Engineering, and Construction (AEC) industry. We commence by presenting succinct expositions on DT: adopting a two-way coupled dynamical conceptual model, and establishing a scaling system for our proposed DT. We then present separately a systematic literature review of the conventional techniques employed in the three civil engineering phases, and the rising role of DT in each phase as a forward-thinking approach in the wake of enabling technologies such as GPU for advanced physics-based and data-driven techniques, computer vision for extended sensing, and Internet of Things for reliable integration. Ultimately, we attempt to reveal DT as an important tool across every civil engineering phase and nudge researchers to think more holistically in their quest for the integration of DT for civil engineering applications.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A 3-D COMPREHENSIVE ANALYSIS OF ADHESIVE MODELS IN A SINGLE LAP JOINT

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ABSTRACT

Industries prefer to join composite materials using adhesive bonding because it offers several advantages over traditional fastening methods. Adhesive bonding plays a pivotal role in enhancing the structural integrity of joints, offering a means to distribute loads effectively and mitigate potential failure modes. Despite the acknowledged importance of adhesive modeling, a notable gap exists in the literature concerning a comprehensive comparison of these methods' crucial outputs. The essence of adhesive bonding lies in its ability to create a robust connection between adherends, redistributing loads and enhancing the joint's overall strength. The choice of modeling technique becomes paramount in accurately capturing the behavior of the adhesive layer within the joint. Our research systematically explores the implications of utilizing cohesive zone model – local and continuum approaches in this context. By elucidating the differences in their outcomes, we aim to provide a foundation for informed decision-making in adhesive modeling strategies. The dearth of comprehensive comparative analysis in existing literature motivates our investigation. Our methodology involves meticulously examining stress distribution, strain patterns, and force-displacement characteristics, systematically comparing the different modeling techniques. This rigorous approach allows for a holistic understanding of their respective strengths and limitations, offering insights that extend beyond the conventional scope of adhesive modeling. Furthermore, our research extends beyond the immediate comparison of modeling techniques. We recognize the multifaceted nature of failure in single-lap joints and aspire to broaden the applicability of our findings. By considering failure modes such as kissing bond, delamination, and disbond, we contextualize our results within a broader framework, enabling researchers and practitioners to extrapolate our findings to diverse real-world scenarios. This abstract encapsulates a comprehensive exploration of adhesive modeling in single-lap joints, addressing a significant gap in the current literature. Our comparative analysis of the different approaches contributes to a deeper understanding of these modeling techniques. This research is poised to inform and guide future endeavors in adhesive bonding, advancing the knowledge frontier in structural mechanics and finite element methods.

EFFECT OF WEIGHT PERCENTAGE OF SILICON CARBIDE ON THE MECHANICAL PROPERTIES AND MICROSTUCTURE OF ALUMINIUM COMPOSITES

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ABSTRACT

The effects of silicon carbide (SiC) addition on the mechanical properties and micro structure of aluminum metal matrix composites are investigated. Aluminum alloy samples with 2%, 4%, 6%, 8%, and 10% SiC composition by weight were fabricated by casting along with a control sample consisting only the Aluminum matrix. The samples were machined to standard specimen for the purpose of Mechanical testing which includes tensile test, hardness test, impact toughness as well as micro- structural examination. The results of the investigations illustrate that the tensile property of the composite is enhanced when the SiC additions are augmented. The 10wt% SiC specimen showed a maximum ultimate tensile strength of 171.85 M Pa and fracture stress of 170.59 M Pa. Hardness also improved proportionally with increased SiC reinforcement, 135.4 Vickers Pyramid Number (HV) was observed for 10wt%compared to 100.2 HV for the control the specimen. However, the impact energy absorbed before fracture by specimens decreased as the SiC reinforcement increased across the specimens. The result shows sufficient Silicon Carbide reinforcement can be applied in Aluminium composites for applications requiring improved strength and lower Impact toughness. Micro graphs detected refined grains and finely dispersed strengthening precipitates for higher SiC compositions which accounts for the superior strength. Spectroscopy analysis for control specimen verified that silicon was the key alloying element. The 10% SiC composite displayed an optimal balance of enhanced strength and hardness coupled with substantial ductility.

Keywords: Silicon Carbide, Aluminum Composites, Casting, Mechanical Testing, Spectroscopy.

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
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ENHANCING PREDICTIVE ACCURACY IN TORNADO COMMUNITY RESILIENCE MODELS THROUGH HINDCASTING AND POST-EVENT RECONNAISSANCE DATA ANALYSIS

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ABSTRACT

Tornadoes present a frequent threat in the USA, resulting in significant physical, social, and economic consequences. These outcomes could be predicted, analyzed, and assessed via community resilience models in helping to formulate strategies to alleviate the impacts. However, models are susceptible to errors that stem from factors such as data availability, quantity and quality, epistemic uncertainty, temporal and spatial scales, variable environmental conditions, and future aleatory uncertainty. These factors could lead to underestimation or overestimation of the effects of tornado hazards, resulting in inaccuracies in predictions and oversights in effective strategies.

Considering these, the accuracy and reliability of community resilience models are investigated in this research by leveraging post-tornado reconnaissance data from communities previously affected by such hazards. Damage assessment data encompassing precise location details, building attributes, structural load path, and observable damage states help in evaluating the accuracy of building performance modules within the larger community resilience framework, further facilitating update, verification, and validation of the model.

Historical data collection is performed followed by model input preparation. Then, a community resilience model is developed, and the outputs are juxtaposed with historical events. This informs the refinement, verification, validation, and updating of the model. Interdependent Networked Community Resilience Modeling Environment (IN-CORE) is utilized for the study, which facilitates modeling natural hazards and community resilience and provides a computational environment for scientific analyses of the impact. To illustrate the proposed methodology, data from a recent tornado event in a US community is implemented. This enabled a comparative analysis of the actual observations against model predictions. The study demonstrates how precise damage information can calibrate and optimize the predictive performance of resilience models. The disparity between actual field damage data and resilience models indicates that resilience models could be optimized. Also, it offers valuable insights into post-tornado assessment strategies, ensuring accurate data is collected for use in resilience models while further enhancing preparedness strategies for future occurrences.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXACT DYNAMIC ANALYSIS OF BEAMS WITH DISTRIBUTED STOCHASTIC PARAMETERS

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ABSTRACT

Dynamic analysis of distributed parameter systems using discretization approaches, such as the finite element method, requires stiffness and mass matrices. Stiffness and mass matrices of beams with stochastic distributed parameters modelled by random fields are considered. In stochastic finite element analysis, deterministic shape functions are traditionally employed to derive stiffness and mass matrices using the variational principle. Such matrices are not exact because the deterministic shape functions are not derived from the exact solution of the governing stochastic partial differential equation with the relevant boundary conditions. This work proposes an analytical method based on Castigliano's approach for a beam element with general spatially varying parameters. This gives the exact and simple closed-form expression of the systems matrices in terms of certain integrals of the spatially varying function. Both Euler-Bernoulli and Timoshenko beams are considered. The expressions are valid for any integrable random fields. It is shown that the exact element matrices of a stochastically parametered beam can be expressed by three basic random variables. It is rigorously proved for the first time that the conventional stochastic element stiffness matrix is a first-order perturbation approximation to the exact expression. Results from the exact system matrices are compared with the approximate conventional matrices. Gaussian and uniform random fields with different correlation lengths are used to illustrate the numerical results. The exact closed-form analytical expression of the element matrices derived here will be suitable for benchmarking future numerical methods.

NEURAL NETWORKS ENSEMBLES OF RESIDUALS TO ACCELERATE POWER GRID CONTINGENCY ANALYSIS

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ABSTRACT

This talk presents an application of Bayesian Graph Neural Networks for power grid contingency analysis. In power grid systems, it is essential to model the effects of potential outages in specific grid elements, such as transmission lines or generators. This contingency analysis can further assist with post-outage response and maintenance of online systems and be an important step in designing new grids. High-fidelity contingency analysis requires solving computationally expensive nonlinear power flow simulations for all possible contingencies of interest. This high computational cost hinders system-wide contingency analysis for higher-order contingencies (multiple simultaneous outages). Alternatively, low-fidelity power flow solvers such as DC approximation offer an approximate solution with a low computational cost. Efficient machine learning (ML) algorithms, such as neural networks (NN), can also be leveraged as surrogate models to speed-up computations. For such high-consequence application however, it is of paramount importance to design ML algorithms that 1) integrate physics information to improve generalization away from training data and 2) embed uncertainty quantification to allow a reliable assessment of our confidence in their predictions. In this talk, we will present some results on the application of Bayesian residual graph neural networks that 1) integrate knowledge about the power grid topology through a NN graph and leverage low-cost physics-based simulations through residual fitting to improve accuracy for out-of-distribution predictions, and 2) quantify uncertainties in predictions via ensembling.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WATER FACILITY MONITORING THROUGH PRE-EXISTING TELECOMMUNICATION OPTICAL FIBER CABLES

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ABSTRACT

Water pumping facilities ensure the proper distribution of inflowing and outflowing water within the city. Deteriorating equipment and chewing at pumping stations are the primary concerns of pumping facilities as this can lead to reduced water pumping efficiency and premature failure. It has been observed that the inefficiency of pumps can lead to up to 45% of the increased cost of maintenance and operation costs. Conventionally, water pumping system efficiency is monitored through devices such as magnetic flow meter that measures the flow rate. However, using magnetic devices is costly and labor-intensive as their installations involve pipeline modification on existing pipelines along with the temporary closure of the water facility.

To this end, we introduce a new water pumping system monitoring approach using the telecom optical fiber cables in a non-dedicated way. Optical fiber cables are laid underground across the city for telecom communication. When light pulses are sent in these optical fiber cables, the light gets backscattered from the impurities in the cable. These backscattered lights are phase-modulated by ground vibrations, such as those induced by traffic or seismic activities. This enables us to sense ground vibrations through the telecom cables, with a range of up to 100 Km along the length of the cable. We use these optical fibers to sense the vibrations created by the water facility on the surface of the earth or buried close to the surface of the earth. Vibrations caused by water pump motors depend on the rotational speed of the motors. According to Affinity law, the rotational speed of the water motor is proportional to the flow rate and thus, is indirectly used to monitor the pumping system. This method of sensing is cost-efficient and can be used for multiple water pumping facilities that are spread across the city. To evaluate our method, we monitored the operation of the stormwater pumping facility at Stanford University for 7 months. The fibers are present 35 m away from the water facility we monitored. We predicted the operational status of the water facility with an accuracy of 99% from the vibration data obtained from these optical fibers.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LIFE-CYCLE MULTI-HAZARD RESILIENCE ASSESSMENT OF TRANSPORTATION NETWORKS

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ABSTRACT

Bridge networks are essential components of infrastructure systems that provide mobility, connectivity, and economic benefits. Bridge networks are essential for the functionality and sustainability of transportation infrastructure systems. However, bridge networks are also vulnerable to multiple hazards, such as earthquakes and floods, that can cause different levels of damage and degradation. In addition, bridge networks are affected by aging and deterioration processes that reduce their structural capacity and performance over time. Therefore, it is important to assess the life-cycle resilience of bridge networks under multiple hazards, considering not only the structural response but also the functional recovery and the socio-economic impacts. This paper presents a framework for life-cycle multi-hazard multi-state resilience assessment of bridge networks, based on probabilistic methods and network analysis. The framework accounts for the effects of deterioration processes and time-variant vulnerability on the structural reliability and resilience of bridge networks. The framework also considers the different states of damage and functionality of the bridge components and the network as a whole, as well as the uncertainties and variabilities associated with the hazard scenarios, the structural models, and the recovery strategies. The applicability and usefulness of the framework are demonstrated through a case study of a bridge network in a multi-hazard-prone region.

Keywords: Life-cycle assessment, transportation network, disaster resilience, multi-state functionality.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIBRATION CONTROL OF HIGH-RISE STRUCTURES EQUIPPED WITH ADAPTIVE STIFFNESS DAMPERS

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ABSTRACT

High-rise structures are exposed to service-level and extreme dynamic loads, such as wind and earthquake, that can induce large vibrations and affect their performance and serviceability. To mitigate the vibration effects, various structural control devices have been proposed and implemented, such as passive, active, and semi-active dampers. This paper proposed adaptive stiffness dampers (ASDs) which are semi-active devices that can adjust their stiffness according to the vibration level and frequency, providing an optimal damping effect. This paper presents a study on the vibration control of high-rise structures equipped with ASDs, based on numerical simulations. This paper compares their performance with other types of dampers, such as tuned mass dampers. The paper also investigates the optimal placement and configuration of ASDs in high-rise structures, considering different loading scenarios and structural characteristics. The results show that ASDs can effectively reduce the vibration response of high-rise structures under various dynamic loads, and improve their sustainability, robustness, and resilience.
Keywords: High-rise structures, Adaptive stiffness damper, semi-active control, vibration control.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

APPLICATION OF MACHINE LEARNING IN STRUCTURAL HEALTH MONITORING OF OFFSHORE PLATFORMS

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ABSTRACT

Offshore platforms are complex structures that operate in harsh environments and are subjected to various loading conditions and degradation processes. Structural health monitoring (SHM) of offshore platforms is essential for ensuring their safety, reliability, and efficiency. However, SHM of offshore platforms poses several challenges, such as limited accessibility, noisy measurements, high dimensionality, and uncertainty. Machine learning (ML) is a powerful tool that can provide data-driven solutions for SHM of offshore platforms, by exploiting the available sensor data and learning the patterns and relationships that characterize the structural behavior and damage. This paper presents a study on the application of ML in SHM of offshore platforms, based on numerical simulations and field data. The paper introduces the main ML techniques that can be used for SHM of offshore platforms, such as supervised, unsupervised, and reinforcement learning, and discusses their advantages and limitations. The paper also investigates the performance of different ML models, such as artificial neural networks, support vector machines, random forests, and deep learning, for various SHM tasks, such as damage detection, localization, quantification, and prognosis. In this study, a dataset of scaled jacket-type offshore platforms is utilized for conducting the SHM with ML. The results show that ML can effectively enhance the SHM of offshore platforms, by providing accurate and robust predictions, reducing the computational cost, and facilitating the decision-making process.

Keywords: Machine learning, jacket-type offshore platform, damage detection, damage quantification.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RESPONSE MODIFICATION OF MOMENT RESISTING FRAMES USING SUSTAINABLE STRUCTURAL SYSTEMS: ROCKING WALLS

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ABSTRACT

The high occupancy levels in urban multistory buildings, in association with current safety considerations inevitably leads to a reconsideration of performance objectives. In view of the appreciable seismic damage and several weak-story failures (some at mid-height) of multistory buildings that have been documented after major earthquakes, there has been a growing effort to develop an alternative hybrid structural system that are not only resilient but also satisfy requirements of being sustainable design.

This paper investigates the inelastic response of a yielding structure coupled with different configurations of rocking walls. The paper first derives the nonlinear equations of motion of a yielding oscillator coupled with a rocking wall. Then, the dependability of the one-degree of freedom idealization is validated against the nonlinear time-history response analysis of a multistory moment-resisting frame that is coupled with a stepping rocking wall. The SDOF idealization presented in this paper compares satisfactory with finite-element analysis of a multi-story building coupled with a stepping rocking wall; therefore, the SDOF idealization can be used with confidence for preliminary analysis and design. The planar response analysis of this paper concludes that for medium-rise to high-rise buildings, vertical tendons in rocking walls are not beneficial. Additionally, in most cases, use of dampers is effective way of reducing maximum deformation in the coupled system; while the additional lever arm for the dampers appears to have marginal effect on the peak response, in particular for taller columns.

Complex dynamics and vibration control of infrastructure exposed to single/multiple hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADAPTIVE TRACKING CONTROL FOR MULTI-AXIAL REAL-TIME HYBRID SIMULATION OF CIVIL STRUCTURES SUBJECT TO EARTHQUAKE LOADING

Andrew Aguila[1], Mariantonieta Gutierrez Soto[1], Alejandro Betancur Palacio[1], Kamal Ahmed[2], Hongliang Li[1] and Ilya Kovalenko[1]*

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ABSTRACT

Understanding the performance of high-rise buildings during extreme events is a challenging engineering problem. Shake bed testing of large-scale structures to test structural integrity is expensive and requires special facilities that can allow for the construction of large-scale test specimens. An attractive alternative is a cyber-physical testing technique known as Real-Time Hybrid Simulation (RTHS), where a large-scale structure is decomposed into physical and numerical substructures. The interface between physical and numerical substructures is created by a transfer system. The challenge occurs when using multiple actuators connected with a coupler (i.e., transfer system) to create translation and rotation at the interface. To account for the complex dynamics, control designers need to develop tracking control systems that improve the time delay of actuators creating the desired displacements. This research proposes two adaptive controllers that allow for multi-axial real-time hybrid simulations and improve capabilities for a higher degree of coupling, boundary, complexity, and noise reduction. One controller combines feedback PID controller with a conditional adaptive series compensation and inverse decoupler. The other controller was developed using a Model Predictive Control approach. The proposed control methods are evaluated using the virtual multi-axial benchmark control problem consisting of a steel frame as the real experimental structure. The transfer system consists of a coupler that connects two hydraulic actuators generating the translation and rotation acting at the joint. Sensitivity analysis was conducted to determine the best tuning parameters for the decoupler, PID controller, and conditional adaptative series compensators. Comparative results among different control methods are evaluated based on performance criteria, including critical factors such as reduction in the time delay of both actuators. In conclusion, these research findings provide improvement in the tracking control systems for the multi-axial real-time hybrid simulation of civil structures during seismic loading. Improving the multi-axial RTHS will allow for the elimination of full testing on structures to see how they stand up against earthquakes. The proposed control design methodologies can be used for managing other multi-dimensional engineering problems and can enable advanced tests on large-scale structural systems.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THIXOTROPY AND RHEOLOGICAL CHARACTERIZATION OF 3D-PRINTABLE ULTRA-HIGH-PERFORMANCE CONCRETE

Ayesha Ahmed[1], Raul Marrero Rosa[1], Shady Gomaa[1], Elmer Irizarry[1] and Gianluca Cusatis[1]*

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ABSTRACT

The utilization of Additive Manufacturing for Ultra-High-Performance Concrete (UHPC) has the potential to transform the optimization of structures by harnessing the exceptional strength and durability inherent in UHPC. However, challenges persist in controlling the rheology of concrete during printing and characterizing its rheological properties. Conventional methods of rheological characterization, such as parallel plate rheometry, encounter difficulties due to squeezing flow and non-uniform shearing in printable concretes. This research investigates the rheological properties of nanomodified 3D-printable UHPC using a cup and stirrer type fixture that facilitates thorough homogenization during shearing. Nano-clay serves as a rheology controller, and the impact of varying nano-clay content on workability, static yield stress, dynamic yield stress, plastic viscosity, and thixotropy has been assessed. The Small Amplitude Oscillatory Shear (SAOS) test was employed to elucidate the material's behavior within the linear viscoelastic range (LVR). The obtained results were then compared with creep recovery tests to illustrate the strain equilibrium and recovery over time under the application of small strains. Furthermore, this work examines the evolution of the mentioned rheological properties with time, identifying the long open time of the developed material-a crucial parameter of additive manufacturing. Finally, this study aims to understand the rheological effects of steel fiber inclusion in the UHPC, for which performing the tests in the rheometer may not be viable due to limitations of maximum torque. Thus, cohesive solid characterization techniques, i.e., direct shear test, confined and unconfined compression tests are performed to study the drastic change in rheology.

Advancements in wind engineering: From atmospheric boundary-layer processes to resilient built environments
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND PRESSURE ON DOUBLE-CURVATURE CABLE DOMES: NUMERICAL ANALYSIS AND COMPARISON WITH CODE PROVISIONS

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ABSTRACT

In addition to their aesthetic appearance, double-curvature (DC) cable domes exhibit superior stability and rigidity compared to their positive-curvature counterparts. Despite these advantages, the significant flexibility and lightweight nature of such structures make them highly sensitive to wind loads. The lack of clear regulations in the current design codes for tensile structures in general, and this form in particular, has motivated the present research to investigate the impact of geometrical parameters on the wind-induced mean and peak pressure distribution on such roofs. Computational Fluid Dynamics (CFD) simulations with Scale-Adaptive Simulations (SAS) turbulence modeling approach, validated with wind tunnel experiment, are performed to investigate the impact of (i) cables and struts arrangements, (ii) structure height off the ground, and (iii) saddle-shaped roof curvature. The results show a negligible effect of cables and struts arrangements on mean and peak surface pressure coefficients. In contrast, a notable sensitivity is observed for both structure height and roof curvature. That is, significant differences are observed when the structure height is changed from 0.1 to 0.4 of the dome span and the saddle roof curvature is changed from 0.1 to 0.25 of the span. The computed gust peak factor show that the non-Gaussianity effect is more pronounced in the flow-detaching regions at the leading and trailing edges as opposed to the central roof area. Further, the structure height has the most significant effect on the peak factor. A comparison with design peak pressure specified in CNR-DT 207/2018 for hyperbolic-paraboloid (HP) roofs is also performed to investigate the adequacy of the code provisions in predicting wind-induced peak pressure distribution on DC cable domes. The comparison shows differences in curvature between DC cable domes and HP roofs, impacting the pressure distribution on the roof. It is recommended to incorporate the findings of this study into the design of DC cable domes in line with the provisions of CNR-DT 207/2018.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING-BASED SURROGATE MODELS FOR SHAPE OPTIMIZATION OF DOUBLE-CURVATURE CABLE DOMES

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ABSTRACT

The real difficulty in designing cable domes is the high sensitivity of these lightweight flexible structures to geometry change. Including the shape parameters in addition to size of all elements and prestress level as discrete design variables in optimization algorithm may lead the algorithm to be computationally prohibitive. In this regard, this study aims at developing simple surrogate functions for a newly developed double-curvature cable dome to predict the optimized level of prestress and the corresponding optimized weight that achieve the target displacement. Different geometrical parameters such as span, number of sectors and hoops, height/span ratio, rise/sag ratio, and inner-hoop diameter are considered. The surrogate functions are developed by training three prediction models, a multi-linear regression (MLR) model, a multiplicative non-linear regression (MNLR) model, and an artificial neural network (ANN) regression model, with the optimized weight and prestress level of a selected dataset of domes' geometries. First, the form-finding of the feasible geometry and base prestress distribution corresponding to each set of parameters is performed. Then, the optimized pairs of weight and prestress level are obtained numerically using a time-efficient incremental-prestressing (IP) iterative technique at three values of target displacement within the allowable limit of design codes. The statistical properties of all prediction models proved their robustness and reliability in predicting the optimized weight and level of prestress, with a superior advantage of the nonlinear surrogate function when synthetically generating a larger dataset of the optimized values. The effect of the uniform load intensity on the developed surrogate functions is also investigated and the results show that well-designed flexible cable domes, where the displacement is too small, behaves linearly and, as such, both the optimized weight and prestress level can be scaled by the load scaling factor. Finally, the effect of the considered geometrical parameters on the optimized weight and prestress level is investigated, providing recommendations for designers.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCEMENT LEARNING FOR MULTI-STABILITY CONTROL OF NONLINEAR DYNAMICAL SYSTEM

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ABSTRACT

Abstract:

The integration of neural networks into Reinforcement Learning (RL) has significantly enhanced the capability to tackle a myriad of control tasks in real-world situations [1]. We employ the canonical Duffing oscillator, known for its sensitivity to initial conditions and the manifestation of diverse behaviors, ranging from multiple coexisting attractors to chaos. The time-evolving state transitions in nonlinear dynamical systems satisfies the Markov Property, enables the application of the Markov Decision Process (MDP) framework, and facilitates the utilization of RL for dynamic system control. We use Deep Deterministic Policy Gradient (DDPG) algorithm [2][3] that operates over continuous state and action spaces, and updates actor and critic neural networks at each time step while randomly sampling a mini-batch from experience trajectories stored in a replay buffer. The primary objective is to control the transition between multiple stable coexisting solutions to achieve the desirable attractor under indeterministic parameters. DDPG is a model-free, off-policy algorithm that does not necessitate a priori knowledge of the system's governing equations, allowing the agent to interact effectively with an unknown environment where state transition probabilities may be stochastic. This versatility extends the applicability of this RL decision making framework to different practical scenarios such as traffic flow, energy harvesting, health care and many more.

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Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPLORING MECHANICAL BATTERY SAFETY IN LITHIUM-ION CELLS UNDER VARIOUS MECHANICAL LOADING CONDITIONS

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ABSTRACT

Within the domain of damage mechanics, understanding the intricate interplay between mechanical behavior and battery safety in Lithium-ion (Li-ion) cells holds paramount importance. This study meticulously explores the mechanical response of Lithium-ion battery (LIB) cells, with a particular emphasis on NMC and LFP types, under both quasi-static indentation and dynamic high-velocity penetration conditions.

Employing a novel approach, a hemispherical indenter is utilized to address existing gaps in stress-strain data for pouch cells, while considering critical factors such as strain rate/load rate and battery cell type. Finite Element Method (FEM) analysis is employed to delve into the mechanical response in two stages: firstly, through the development of a viscoplastic model to predict the indentation test, followed by the formulation of a thermomechanical model to anticipate high-speed impact penetration.

An essential facet of this research lies in the integration of damage mechanics principles into the study of battery safety. By incorporating adiabatic heating effects to account for the high plastic strain rate of LIB cells, the study addresses the intrinsic damage mechanisms influencing mechanical behavior during deformation. Notably, a significant reduction in force is uncovered when transitioning from a single cell to a stack of two cells, underscoring the importance of comprehending damage mechanics in stacked configurations.

Furthermore, the utilization of the Johnson–Cook material model and quasi-static testing enables the prediction of mechanical behavior of pouch cells during high-velocity penetration experiments, thereby establishing a correlation between damage mechanics and mechanical safety in battery cells. This comprehensive exploration not only contributes to the understanding of damage mechanics in LIB cells but also enhances safety considerations and advances predictive models for their mechanical behavior.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZING URBAN FLOW DISTURBANCES FOR SAFE UAM OPERATIONS USING HIGH RESOLUTION LARGE-EDDY SIMULATION

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ABSTRACT

The operation of urban air mobility (UAM) vehicles within urban environments can be strongly affected by atmospheric disturbances due to their small inertia and low flight speed and altitude. These disturbances not only potentially jeopardize the safety of UAM, but also impact the noise produced during flight. Although several studies have been done to simulate flow within idealized or realistic urban settings, but little has been done to characterize the flow disturbances for UAM near rooftops of buildings that could serve as a vertiport and in the wake of buildings. To bridge this knowledge gap, we perform large-eddy simulations of flow over idealized (e.g., aligned cubes, slender and wide buildings) and realistic urban settings to characterize the flow disturbances near building rooftops and downstream of buildings for various scenarios (e.g., wind speeds, wind direction, and stable or unstable stratifications). This study can help design safe and low-noise future UAMs.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GROUND PENETRATING RADAR DIAGNOSTICS FOR BUILDING ENVELOPES: A DATA-DRIVEN APPROACH

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ABSTRACT

Ground Penetrating Radar (GPR) is an essential tool in nondestructive evaluation and structural health monitoring. GPR has been applied with great success to geological surveying and assessment of subsurface infrastructure, such as roadways, buried pipes and cables, and rebar embedded within reinforced concrete. However, a significant area of opportunity for GPR is the diagnostics of building envelopes, for which this technology has been relatively under-utilized.

Building envelopes present a specialized set of challenges for radar-based diagnostic techniques. The low permittivity contrast between different construction materials results in a low signal-to-noise ratio and makes it difficult to distinguish relevant features from clutter. The diverse range of potential geometries and defects also introduces a wider range of signal patterns compared to rebar detection, for instance, making this problem more challenging. Finally, building envelopes often contain geometries that are smaller than the characteristic wavelength of radar waves (e.g., 5-10 cm), leading to challenges related to resolution limits.

In this work, a data-driven approach is proposed to address some of these technical challenges. A small dataset of field scans obtained from a residential building envelope with known interior geometry is presented. The data are pre-processed and projected to reduced dimensional space using a neighborhood-based approach. The transformations yield a more interpretable data space, where envelope sections requiring diagnostic attention are easily recognized as outliers in the distribution. Furthermore, we present developments in our supervised learning approach to effectively invert radargrams to spatial permittivity maps, enabling detailed diagnostics for building envelopes.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROCESS MODELING AND CHARACTERIZATION OF A QUASIBRITTLE CARBON FIBER USING MOLECULAR DYNAMICS

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ABSTRACT

High Strain Composite (HSC) laminates have the exceptional ability to withstand extensive deformation under curvature loading, making them an ideal material for large-scale deployable space structures. As the demand for large-scale space structures increases, the need arises to package these structures into compact volumes, which necessitates a comprehensive understanding of their failure mechanisms. Unlike standard composites, the failure mechanisms of HSCs in flexure have been shown to be highly dependent on the fiber constituent properties in the large strain regime. However, conducting single fiber tests, under complex loading conditions to investigate the material properties of the overall HSC laminate structure is practically infeasible due to the complex nature and small size scales of the individual fibers (6 µm fiber diameter).

This research explores the utilization of molecular dynamics for process modeling and subsequent virtual testing to infer the nonlinear and fracture properties of a PAN-based carbon fiber. The computational framework seeks to gain insight into the intricate nano-structure of PAN fibers and its loading mechanics under different boundary conditions. First, the nano-structure of the PAN fiber is generated. This is composed of compact folds of graphitic sheets, where the details of the fold-lines and internal flaws are induced during the process of carbonization and graphitization [1]. The first step in the analysis will include replicating the manufacturing processes of the fibers in order to capture the intricate details of the PAN fibers at the nano-scale [2].

The second step will include applying mechanical loads on the generated nano-structure in order to infer the nonlinear stress-strain response and the fracture properties. During the loading process, the relative shifting of the graphitic plates and their interactions with internal flaws plays a critical role in the material response. The loading cases that are of interest include tension, compression, and bending.

The findings of this research are expected to significantly enhance the design and optimization of large-scale deployable space structures. A better understanding of nonlinearity and the quasibrittle fracture mechanism of PAN fibers will allow for tailoring the material properties of HSC for specific applications, ensuring their structural integrity and performance in space environments.

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Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVOLUTIONARY GENERATIVE AI FOR MECHANICAL METAMATERIAL DISCOVERY

Wenyun Lu[1], Jianzhe Luo[1], Daeik Jang[1], Qianyun Zhang[2] and Amir Alavi[1]*

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ABSTRACT

We present recent advancements in our research focused on utilizing generative artificial intelligence (GAI) based on evolutionary computation for accelerating the discovery and design of cementitious mechanical metamaterials. In contrast to conventional GAI methods relying on neural networks and backpropagation, our proposed evolutionary GAI incorporates principles inspired by biological evolution to iteratively generate and refine representative unit cells, leading to the identification of entirely novel and previously unknown material properties. This approach aligns seamlessly with the core objective of GAI, which is to create original and unseen data, in this case, metamaterial models. Here, we initially define maximum bulk modulus and minimum Poisson's ratio as singular objective functions for the evolutionary GAI search to discover lattices with high compressive and flexural strength. Subsequently, a multi-objective function, incorporating both bulk modulus and Poisson's ratio, is employed to explore lattices with tunable compressive and flexural strength. We fabricate a range of cubic and beam-shaped lattices using concrete mixtures with fine aggregates and subject them to mechanical testing to evaluate their properties. Further discussions are presented to elaborate on how the proposed methodology can play a crucial role in designing civil infrastructure systems that are not only strong and durable but also significantly lighter, contributing to enhanced sustainability.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIRELESS FORCE SENSING WITH MECHANICAL METAMATERIALS

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ABSTRACT

Integrating extra electronics, wiring, and power supply components poses substantial challenges when aiming to minimize the dimensions of conventional force sensors. These complexities have hindered the widespread adoption of force sensors in various fields such as robotics, healthcare, and smart implants. To address these challenges, we propose an innovative wireless force sensing approach through the integration of mechanical metamaterials and nano energy harvesting technologies. We demonstrate composite mechanical metamaterial systems capable of serving as all-in-one wireless force sensing units, incorporating functions for power generation, sensing and transmission. The proposed approach is founded on the concept of meta-mechanotronics recently proposed for active sensing, energy harvesting and information processing with mechanical metamaterials. We show how the strain-induced signal produced by the composite meta-mechanotronic lattices under mechanical triggering can then be detected wirelessly by external electrodes. The practicality of the proposed wireless force sensing approach is demonstrated through a proof-of-concept orthopedic implant. The findings indicate that the meta-mechanotronic implant with low power output on the order of 0.1 pW allows for mid-range wireless communication (<3 m) during force sensing across air, simulated body fluid, and animal tissue. Further insights are provided on the potential of the proposed approach for crafting mechanically-tunable structures that can accurately measure forces and wirelessly transmit real-time data, all without relying on any external antennas, power sources or telemetry systems.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATIONAL DESIGN APPROACHES FOR TAILORING THE RATE-DEPENDENT RESPONSE OF SOFT METAMATERIALS EXHIBITING INSTABILITIES

Ryan Alberdi[1], Craig Hamel[1], Aabhas Singh[1], Adam Cook[1] and Kevin Long[1]*

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ABSTRACT

In the last decade, research on soft metamaterials has revealed a rich set of behaviors driven by large geometric and symmetry changes in response to external stimuli that trigger instabilities. More recently, several studies have highlighted how viscoelastic relaxation effects alter the emergence of these instabilities. As many 3D printed elastomers exhibit significant viscoelastic relaxation, this has a large influence on the design of soft metamaterials for applications where the loading rate is non-trivial. Moreover, the interplay between loading rate and geometric instabilities can lead to new avenues for soft metamaterials including extreme hysteresis and rate-dependent configurational switching. These ideas are only beginning to be explored and require the development of rigorous design tools that can be used to explore a design space where intuition is lacking. We propose an approach for computational design of soft metamterials that can robustly handle instabilities while accounting for the path-dependence of viscoelastic phenomena. To do this, we utilize a unique library for solving nonlinear solid mechanics problems that poses them in an energy minimization form and uses a trust region algorithm to handle saddle points and differentiate between stable and unstable equilibria. Examples are presented to demonstrate how the rate-dependent response of soft metamaterials undergoing snap-through and buckling instabilities can be tailored through parameterized shape optimization.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STABILIZED EXTENDED B-SPLINE MATERIAL POINT METHOD FOR MULTI-FIELD SOFT MATERIALS WITH NITSCHE IMPOSITION OF BOUNDARY CONDITIONS

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ABSTRACT

Material point method (MPM), a hybrid Eulerian-Lagrangian particle-based continuum method, is a promising alternative to the traditional mesh based finite element method due to its robustness in handling extreme deformations and no-slip contact without additional algorithmic treatment. The use of B-spline shape functions in MPM effectively mitigates the classical numerical artifacts typically associated with linear shape functions, such as artificial fractures and cell crossing instabilities. Implicit MPM is preferred in modeling highly deformable materials like elastomers, hydrogels and biological tissues often characterized and used under quasi-static conditions. However, the B-spline MPM approach faces challenges with the ill-conditioning of stiffness matrix in implicit models, due to fewer material points at boundaries, and complexities in imposing boundary conditions. Furthermore, modeling at quasi-compressible limit, for coupled problems such as capturing large deformations along with water transport in hydrogels, require development of inf-sup stable mixed methods [1]. Here, we resolve these challenges using a subdivision stabilized mixed formulation, and further extending the subdivision-technique to extended B-spline technique, in addition with exploiting the Nitsche method for imposing boundary conditions. The extended B-spline shape functions addresses the ill-conditioning, where the displacement and pressure (or chemical potential) fields near the detected physical boundaries are interpolated to the interior ones using polynomials. The subdivision-based extended B-spline method achieves an oscillation-free, inf-sup stable mixed discretization in modeling nearly incompressible materials, such as elastomers or hydrogels, under instantaneous loading. Through the use of Nitsche method, essential and natural boundary conditions are weakly imposed directly on the Lagrangian particles, instead of the Eulerian background grid where the solution is obtained. The stability and accuracy of our mixed B-spline MPM is tested at extreme deformations and verified by comparing our result with benchmark problems, including incompressible cylindrical elastomer and hydrogels with a cavity inside under pressure loading. These examples showcase the effectiveness of developed particle-based method in modeling practical soft material applications without any numerical instabilities.

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Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TWO-STAGE OPTIMIZATION APPROACH FOR AUTOMATED UAS STRUCTURAL VISUAL INSPECTION MISSION PLANNING

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ABSTRACT

Effective mission planning is pivotal in ensuring reliable structural inspection outcomes using Unmanned Aerial Systems (UAS). In manually planned structural inspection tasks, the quality of inspection results significantly relies on the experience and expertise of the pilot. To enhance the automation and robustness of structural inspections, this study proposed an autonomous mission planning framework optimizing path length under quality and coverage constraints to maximize efficiency while ensuring safety, performance, and comprehensiveness. The algorithm comprises a genetic optimization algorithm for path planning and a greedy algorithm for determining camera poses. This division allows for the resolution of the mission planning problem in two distinct yet interrelated parts, which decreases the computational expense and improves the optimization results. Sensitivity analysis was conducted on the proposed algorithm to demonstrate its adaptability across various parameters. Finally, the technique for controlling the UAS along the generated path was introduced, and a real-world demonstration illustrated the feasibility of the proposed method. In summary, the findings of this study emphasize the practicality of the proposed mission planning method and lay the foundation for integrating automation into mission planning for structural inspections using UAS.

DISCRETE MODELING OF THE CONCRETE BIOSHIELD LONG-TERM PERFORMANCE IN LIGHT WATER REACTORS

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ABSTRACT

The International Energy Agency reported in its Net Zero by 2050 Roadmap that the scale of nuclear electricity generation within the next 30 years needs to be doubled. Therefore, maintaining the current nuclear power plant fleet operational and even extending its lifespan is of prime importance. One of the major elements determining the lifespan of Light Water Reactors (LWRs) is the concrete bioshield (CBS). The CBS is a thick reinforced concrete structure that surrounds the Reactor Pressure Vessel (RPV). Its main purpose is to provide protection for equipment and personnel from the radiation exiting the RPV and may be used to provide structural support for the RPV in some LWRs designs. Radiation fluxes induce different degradation processes within the CBS. The most pronounced effect is the influence of Neutron radiation on the minerals within the aggregate. Neutron radiation induces amorphization of the crystalline phases in such minerals resulting in a so-called Radiation Induced Volumetric Expansion (RIVE). This causes the aggregate to degrade and induces internal pressure that propagates within the interior surface of the CBS. Over the past years, researchers have been performing several experimental campaigns to understand the kinetics of such degradation mechanisms and their coupling with mechanical stresses and thermal effects. The most agreed-upon understanding is that the ultimate result of RIVE is a loss of the CBS material strength and elasticity. The nature of the aggregate minerals, its heterogeneity, and the general heterogeneity of concrete all pose challenges in resolving the interplay between material composition, its mechanical strength, and its degradation due to RIVE. Given the expensive and challenging nature of performing irradiation experiments, the amount of experimental evidence is not enough to fully understand the coupling and interplay of the different conditions. Additionally, given the lack of cored samples from long-term operating LWRs, designers and regulators must depend on theoretical and computational models to predict the useful service life of the CBS in order to evaluate both safety and possible future licensing. In this presentation, detailed simulations of the effects of RIVE on the CBS long-term behavior up to 80 years will be presented. An evaluation of its damage degree will be discussed under service and accidental conditions showing the superiority of discrete models in describing a more realistic damage measure than continuum models. It will be shown that at such small scales and significant gradients, the continuum assumptions seem to not realistically hold anymore.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEASONALLY FLUCTUATING STRENGTH OF SOILS IN MID-WESTERN USA AND CPT BASED QUANTIFICATION METHOD

Bashar Al-Nimri[1] and Chung Song[1]*

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ABSTRACT

Research has shown that several roadside slopes in the Mid-Western states of the USA slowly move and fail even though engineers designed and constructed them properly. The back-calculated strength of soils for the failed slopes was much lower than the measured one during the design stage. When the soil was saturated and the effective overburden pressure was released, the magnitude of strength reduction of soils at failed slopes ranged from 22% to 90% of the initial strength.

This kind of significantly reduced strength is called “wet-drained-fully softened strength”. The fundamental mechanism of this critical strength is the coupled interaction of precipitation-micro mineralogy and stress history of these clay particles. The reproduction of this “wet-drained-fully softened (WDFS)” condition in the lab is highly time-consuming and prohibitively expensive.

The research utilized a modified Piezocone device that generated a “wet-drained-fully softened strength” condition in the field and incorporated the drainage effect to obtain this critical strength. The measured results showed a very rational match with soil strength data from failed slopes in the Lincoln area.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FLOATING RESONANT ABSORBER FOR CONTROLLING VIBRATION OF OFFSHORE FLOATING WIND TURBINES

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ABSTRACT

This work proposes a novel concept of floating resonant absorber for the motion mitigation of multi-megawatt floating offshore wind turbines. Usually, classical tuned mass dampers are adopted with the purpose of controlling the motion of floating wind turbines. To this end, devices are placed within the nacelle or inside the support structure. However, limited mass device can be used due to space availability and to avoid excessive dead loads on the floating wind turbine. This results in low efficiency and very large relative displacements required between the mass device and the wind turbine structure. The proposed floating absorber, instead, is thought as a spar floater that floats independently of the floating wind turbine, allowing for very large mass device. The floating absorber is connected to the floating wind turbine support structure by a parallel spring-dashpot, as in classical tuned mass dampers. The floating wind turbine considered in this study is the NREL 5MW wind turbine on the Hywind OC3 spar. A simplified model of the floating wind turbine and of the floating absorber is developed for the numerical assessment of the proposed solution. The parameters of the spring and of the dashpot are calibrated by a modified version of the fixed point procedure applied to the developed simplified model. Extensive numerical simulations are performed with several combinations of mean wind speed and see state on various geometrical layouts of the floating absorber. Results of numerical simulations demonstrate that the proposed solution is very efficient both in operational and parked (cut-out) conditions, mainly thanks to the high device mass adopted. Further, it is seen that for fixed mass of the absorber the efficiency of the floating absorber in reducing the pitch motion of the floating wind turbine is basically independent of the adopted geometrical layout, making the proposed solution very flexible. Remarkably, numerical simulations have shown also that relative displacements between the floating wind turbine and the floating absorber are reasonable for potential real applications.

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SCALING EFFECTS OF A BISTABLE PIEZOMAGNETOELASTIC NON-LINEAR ENERGY HARVESTER

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[1]Stevens Institute of Technology

ABSTRACT

Modern technology in many applications relies on the development of low-power autonomous sensing and measurement microsystems. One constraint of battery-powered sensors is the short lifetime of their batteries. With the availability of background vibrations, the conversion of mechanical energy into electrical energy using piezoelectric materials is a promising alternative to develop sensors and other devices that would not require changing batteries. Although adopting linear energy harvesters that operate near their resonant frequency is effective in one sense, such systems may not take full advantage of the broad frequency spectrum of ambient vibrations. Many investigations have aimed at broadening the capability of piezoelectric energy harvesters by inducing nonlinear phenomena with the expectation of enhancing the harvested power by widening the harvester's bandwidth.

We perform a numerical investigation of the performance of a bistable piezo-magnetoelastic non-linear energy harvester to assess scaling effects by considering the variations in its energy density with its characteristic size and mass. The harvester is modeled as an Euler-Bernoulli cantilever beam with a magnetic tip mass where a fixed magnet is placed horizontally in front of the tip magnet. The top surface of the beam, acting as a substrate, is partially covered by a macro fiber composite (MFC) piezoelectric layer for energy harvesting when the harvester is laterally excited at its base. The finite difference method is used to discretize the electromechanical voltage equation which is coupled with the beam equation of motion. The finite element method is implemented to solve the coupled time-dependent system with an implicit solver for time integration using the strong coupling approach for the nonlinearity introduced by the tip-deflection-dependent magnetic force. The performance metrics include the harvested electric power, the effect of the distance between the magnets, and the force potential.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advancements in wind engineering: From atmospheric boundary-layer processes to resilient built environments
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING WIND RESILIENCE IN PHOTOVOLTAIC SYSTEMS: INTEGRATING CFD SIMULATIONS, DESIGN STANDARDS, AND EXPERIMENTAL INSIGHTS

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ABSTRACT

This study addresses the wind resilience for photovoltaic (PV) systems, offering a nuanced exploration of Computational Fluid Dynamics (CFD) simulations, design standards, and experimental testing. Beginning with an evaluation of ground-mounted solar panels, the study produces CFD results versus design standards, providing an in-depth analysis of wind loads in a solar farm case study. The investigation encompasses the nuanced impact of different American Society of Civil Engineers (ASCE) design standard versions, complemented by a cost-benefit analysis highlighting potential cost reductions in the wake of natural disasters. The second dimension focuses on resilient PV systems, bridging CFD and machine learning (ML) to determine optimal design wind loads. Experimentally validated CFD simulations, deviating from traditional practices, advocate for a strategic -15° stowage angle during wind events. The integration of ML and CFD accelerates simulations exponentially, offering an efficiency boon for wind engineering applications. The final aspect delves into experimental testing of roof-mounted solar panels integrated with buildings. Wind engineering relevance is emphasized with findings showcasing a substantial reduction (45–63%) in wind-induced forces. This research delivers holistic insights crucial for wind structural engineers aiming to fortify the resilience of PV systems in the face of dynamic wind forces.

Keywords. Wind Resilience, Photovoltaic Systems, Computational Fluid Dynamics (CFD), Wind Structural Engineering, Design Standards, Experimental Testing.

Advancements in wind engineering: From atmospheric boundary-layer processes to resilient built environments
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL SIMULATION OF FLUID-STRUCTURE INTERACTION BASED ON DIFFERENT COUPLING MECHANISMS: A PARAMETRIC STUDY

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ABSTRACT

Fluid-structure interaction (FSI) problems occur when a structure is in contact with a fluid flow, causing the flow forces to induce motion in the structure. One-way FSI and two-way FSI are two coupling mechanisms in FSI modeling which differ based on the data transformation and how the solvers are coupled. Moreover, each of these mechanisms has limitations and capabilities, making FSI simulation challenging as there should be a balance between problem simplification and computational cost. This paper aims to address this challenge by comparing one-way FSI and two-way FSI for simple structures. To this aim, a three-dimensional simulation has validated an FSI investigation consisting of laminar incompressible channel flow around an elastic beam connected to a rigid cylinder. A comprehensive parametric study was conducted considering benchmark configurations. Three different beam lengths are considered to evaluate the effect of structural flexibility. Moreover, different flow velocities are considered to investigate the role of Reynolds number. A comparison among different cases focused on accuracy and time efficiency.

Keywords: Computational Fluid Dynamics (CFD), Fluid-Structure Interaction (FSI), Two-way coupling, Flow-induced deformation.

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATING THE INFLUENCE OF SEISMIC MITIGATION MEASURES ON THE PERFORMANCE OF CHILEAN BRIDGES

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ABSTRACT

Highway bridges are critical structures for the operation of transportation networks; therefore, it is necessary to guarantee their safety and functionality. Particularly in regions of high seismic risk, it is essential to implement robust engineering measures to enhance bridge resilience and ensure their continued operation during seismic events. In the case of Chile, after the 2010 Mw 8.8 Maule earthquake, significant regulatory changes were introduced with the aim of mitigating seismic damage and preventing the collapse of bridges. This research evaluates the influence of different seismic mitigation measures considered in the Chilean bridge design code. Those measures include the incorporation of anchorage in elastomeric bearings, the use of internal and external shear keys, the use of vertical seismic bars, and the incorporation of diaphragms. A typical Chilean simply supported prestressed concrete girder bridge is used as a case study. 3D nonlinear numerical models of the bridge, both before and after the incorporation of the seismic mitigation measures, are developed using OpenSees. The bridge models are subsequently subjected to a suite of ground motion records obtained from a regional seismic hazard assessment. The efficiency of the mitigation measures is assessed in terms of the change of the seismic fragility and the reduction of seismic risk metrics. The findings of this research illustrate the implications of the changes in seismic design and provide crucial insights for the decision-making process on how to enhance the seismic resilience of Chilean bridges.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INNOVATIVE COMPUTATIONAL STRATEGIES FOR COASTAL RESILIENCE: TACKLING HURRICANE-INDUCED DEBRIS CHALLENGES

Kooshan Amini[1], Yuhao Liu[1], Jamie Padgett[1], Ashok Veeraraghavan[1] and Guha Balakrishnan[1]*

[1]Rice University

ABSTRACT

As the severity and frequency of climate-related hazards, particularly hurricanes, escalate, coastal communities are increasingly facing significant challenges. These events, beyond causing substantial economic and social disruptions, also lead to complex situations involving large-scale, hurricane-induced debris. This debris significantly impacts critical infrastructures and disrupts key community systems such as transportation and utilities. In light of these challenges, the potential of artificial intelligence (AI) and deep learning in modeling the intricacies of debris and its broader implications is becoming more evident. Currently, an adaptive computational framework is being developed by a multi-disciplinary team, harnessing the power of AI and deep learning in this context. Project team, comprising experts from various fields, collaborates to enhance the framework's effectiveness. The framework itself is deliberately designed to be flexible, allowing for ongoing modifications and enhancements. It incorporates techniques such as Convolutional Neural Networks (CNN) and image segmentation, utilizing a diverse array of datasets, including high-resolution aerial images and extensive data from built, human, and natural environments. This framework is envisioned to offer dual benefits. Initially, it aims to create a model for immediate post-hurricane analysis, focusing on identifying debris locations and volumes. This information is crucial for streamlining debris removal operations, estimating costs, and managing emergencies effectively. Moreover, the framework is also geared towards developing a predictive model for future hurricane scenarios. This model is expected to aid in formulating mitigation strategies and enhancing risk management. While the results are still in the preliminary stages, the expected outcomes are promising. We anticipate that this framework will significantly deepen our understanding of debris dynamics and their impacts on coastal communities. The primary goal is to enhance disaster preparedness, expedite recovery processes, and fortify the long-term resilience of communities in high-risk areas. This project marks a significant advancement in disaster management, emphasizing debris detection and prediction. It showcases the importance of cutting-edge technologies and multi-disciplinary collaboration in addressing environmental challenges, with a framework designed for dynamic adaptation to evolving climate hazards and technological progress.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PINN METHOD FOR REGISTRATION OF MEDICAL IMAGES

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[1]Purdue University

ABSTRACT

In this work, we introduce a novel machine-learning framework for the registration of medical images. Our approach is based on principles of continuum mechanics in the context of large deformation theory. In the first part of the approach, similar to existing methods in the literature, we formulate the registration problem in terms of minimization of a multi-objective loss function consisting of a metric that measures the similarity and a small regularization term enforcing the smoothness of the resulting transformation. The resulting 'predictor deformation field' is the departure point for the corrector part of our method, where we impose equilibrium equations in a weak sense.

To this end, we define a Dirichlet boundary value problem whose displacement boundary conditions are defined by the aforementioned 'predictor deformation field.' Subsequently, we follow a procedure similar to the finite element method and minimize the potential energy corresponding to the Dirichlet problem mentioned above, where the variation of the corrector solution is enforced to vanish on the boundary points by employing the distance function. This solution form maintains the registration achieved in the predictor part while obtaining the stationary point of potential energy, thus weakly fulfilling the equilibrium equations. In contrast to the finite element scheme in which the problem is defined in terms of the displacement field, we follow a flow algorithm where a first-order ODE governs the deformation. This specific form inherits strong expressibility to capture the solution while securing the invertibility of the resulting transformation.

In our presentation, we first explain the foundations of the new approach and specifically how the new method follows steps similar to the finite element approach. We then focus on examples that result in a non-uniform displacement field to reveal features of the new method. On the application side, we quantify the deformation in zebrafish tails observed in microscopic image data. Subsequently, the registration of a pair of 3D MRI scans of brain atrophy, in which a deformation-independent ODE governs the shrinkage phenomenon of the brain with disease, is discussed. Finally, we present our analysis regarding the 3D skin growth phenomenon. The growth mechanism is dictated by a first-order ODE, which depends on the deformation gradient, whose parameters have been measured experimentally in our previous work.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ESHELBY INCLUSION-BASED TECHNIQUE FOR MODELING HETEROGENEOUS ELASTIC FORMATIONS UNDER THE CONDITION OF INCOMPLETE FIELD DATA

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ABSTRACT

This paper presents the novel Eshelby inclusion-based technique for modeling heterogeneous elastic formations. In the technique, the heterogeneities are represented by the regions of stress-free transformational strains (eigenstrains). It is assumed that the geometrical shape of the region is known, but the data on the eigenstrains is only available at the number of discrete points at which, e.g., the measurements are performed. The region of interest is discretized using the triangulations procedure in which the points with known data are made to be located at the vertices of the triangles. It is assumed that the eigenstrain distribution inside each triangle is uniform, but different from that inside other triangles. The value of that uniform eigenstrain is evaluated by constructing a linear interpolating function from the values at the triangle's three vertices and by finding the average of that function over the area of the triangle. The elastic fields and the components of the Eshelby tensor both inside and outside of each triangle of the region of interest are obtained from exact complex variables-based integral representations for the relevant fields. The technique is validated by comparisons with the reported benchmark results for problems involving circular inclusions subjected to prescribed nonuniform eigenstrains and with those involving inclusions of arbitrary shapes subjected to prescribed uniform eigenstrains. Presented numerical examples showcase the potential of the technique in handling the problems involving arbitrary-shaped inclusions subjected to nonuniform eigenstrains whose values are available at the discrete number of points.

IMPACT-DRIVEN ELECTROMAGNETIC ENERGY HARVESTER WITH DUAL RESONATORS

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ABSTRACT

In recent years, energy harvesting has become a crucial element in the sustainable design of transportation infrastructures. This is primarily attributed to the role of energy harvesting in advancing environmentally friendly technologies capable of harnessing electric power from clean sources, such as the vibration induced by traffic on these infrastructures. Energy harvesting offers the potential to transform this kinetic energy into electric power, which can be used to power wireless sensors and other electronic peripherals essential for detecting damage and assessing the condition of transportation infrastructures. However, a challenge arises from the low-frequency vibrations typically observed in bridges under daily traffic, ranging from 5 Hz to 10 Hz. Energy harvesters with a low and narrow-band resonant frequency often generate minimal electrical power under such conditions. This is because the generated power is directly proportional to the cube of the frequency of vibration.

The objective of this study is to investigate the efficiency of a mechanical impact-driven and frequency up-converted electromagnetic energy harvester with dual resonators. The aim is to convert the vibration induced by traffic into electric power at higher frequencies by broadening the resonant frequency band. The proposed energy harvester consists of three stationary layers of rectangular magnets with alternating-pole arrangements and two thick rectangular copper coils attached to the free ends of two flexible cantilever beams, serving as resonators whose fixed ends are firmly attached to the bridge oscillating in vertical direction during passing traffic. To create a mechanical impact, two rigid stoppers are inserted at the free ends of the resonators to constrain their displacements at a specific gap. As the system experiences vibration, the resonators come into contact with the rigid stoppers which results in an increase in the stiffness of the cantilever beams. This change transforms the linear oscillation of the resonators into a nonlinear impact oscillation due to the displacement constraints imposed by the rigid stoppers. The numerical and laboratory testing of a proof-of-concept prototype for the proposed energy harvester reveals its capability to generate an average electrical power exceeding 100 mW across a wide resonant frequency band over a one-second period. This amount of electric power is adequate to power a standard wireless accelerometer.

Using pavement mechanics to develop pavement materials with less environmental impact
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANISTIC-EMPIRICAL DESIGN AND LONG-TERM PAVEMENT PERFORMANCE PREDICTION OF POROUS FLEXIBLE PAVEMENT EMPLOYING WARM-MIX ASPHALT

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ABSTRACT

Porous asphalt pavements are becoming increasingly popular as a sustainable and innovative solution for reducing stormwater runoff and the heat island effect in urban areas. Porous pavements have traditionally been constructed using Hot Mix Asphalt (HMA), which is heated and poured at temperatures ranging from 300 to 350 degrees Fahrenheit. However, Warm Mix Asphalt (WMA) has recently been used for the same, which is produced at temperatures ranging from 200 to 250 degrees Fahrenheit. This type of mix is characterized by having a coarse-textured, open-graded surface and a high, interconnected air void content throughout. It uses less fossil fuels and resources which is better for the ecosystem and worker health as it is poured and set at lower temperatures, there is less dust, smoke, and fumes. To reduce this temperature, Cecabase has been used, which is an asphalt additive that allows for easier field compaction, strong adhesion of the asphalt binder to aggregates, and improves the workability of asphalt mixtures, with no change in the bitumen grade. This abstract outlines a comprehensive study on the mechanistic-empirical (M-E) design and long-term performance prediction of porous flexible pavements incorporating warm-mix asphalt (WMA). The research aims to address the environmental and structural challenges associated with traditional pavement systems by leveraging the benefits of WMA and the porous design. The mechanistic-empirical (M-E) design principles laid by IRC-37 (Indian Roads Congress Code for the design of flexible pavements) have been followed for the design of porous pavement. The long-term pavement performance in terms of roughness progression and expected deterioration (cracking, ravelling, etc.) in the pavement was assessed using the project analysis system of the Highway Development and Management tool (HDM-4). A sample porous pavement section was created in HDM-4 using the attributes of an open-graded warm mix asphalt material as obtained from the laboratory investigation. The section's long-term performance was analyzed for an operation period of 25 years and the progression in deterioration was estimated. The results indicate an improved resistance to cracking, ravelling, formation of potholes, etc. which could be attributed to the improved drainage provided by the porous structure of the pavement and a few other factors as well. However, it is also essential that the validation of the HDM-4 output should be done on a sample pavement section by conducting an in-situ performance test of the sample porous pavement employing warm-mix asphalt.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRAIN-BASED OMA AND QUASI-STATIC RESPONSE MONITORING OF A VIERENDEEL TRUSS RAILWAY BRIDGE

Dimitrios Anastasopoulos[1], Kristof Maes[1], Geert Lombaert[1] and Edwin Reynders[1]*

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ABSTRACT

Strain-based monitoring methodologies can offer the crucial advantage of early stage damage detection due to the large effect that damage can have on the strain field in its immediate vicinity [1]. For this reason though, a dense sensor grid is required that can provide relevant information in several critical locations of the monitored structure. In this work, it is demonstrated that both static and dynamic monitoring can be performed with the same long-gauge strain monitoring system, if the accuracy of the system is of the sub-microstrain level. Hence, two strain-based methodologies are explored in detail and the complementarity and accuracy of the resulting information is assessed. A historical Vierendeel truss bridge in Belgium serves as the test structure. The strain measurements are conducted with a fiber-optic sensing-based methodology that has been successfully implemented on other bridges [2,3] and makes use of a dense grid of standard fiber-Bragg gratings (FBG) and an interrogator of high accuracy and precision. The first methodology is based on ambient dynamic strain measurements, which are used in automated Operational Modal Analyses (OMA) to obtain the modal characteristics of the bridge, i.e., strain mode shapes, natural frequencies and damping ratios, continuously and with high accuracy. The second methodology is based on (quasi-) static strain measurements during train passages, which are used for calculating the strain influence lines of the bridge. The sensitivity of the employed monitoring quantities to relevant types of damage, e.g., fatigue cracks, is investigated through numerical simulations and compared to this of environmental and operational factors, such as temperature and loading amplitude.

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Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STUDY OF CORE SPLICING CONFIGURATIONS IN A COMPOSITE SANDWICH STRUCTURAL SYSTEM USING EXPERIMENTS AND COMPUTATIONAL METHODS

Rawan Aqel[1], Patrick Severson[1] and Rani Elhajjar[1]*

[1]University of Wisconsin - Milwaukee

ABSTRACT

The study focuses on enhancing composite sandwich structures by introducing a novel core splice joint configuration for thick aluminum-based honeycomb cores with carbon fiber and epoxy matrix facesheets. They investigate dovetail joints with varied angles compared to conventional straight-core splices. Experimental and numerical analyses assess mechanical behavior under bending and shear forces, evaluating stress distribution and strength. Results indicate a 13% to 51% strength increase and a 2% to 35% toughness improvement in dovetail joints compared to standard straight joints.

Dovetail joints offer a smoother load transfer path in composite constructions. Finite element modeling highlights reduced stress in splice materials and core/splice interfaces with certain dovetail tenon lengths (15-30 mm) and angles (70-80 degrees). Experiments show higher strength and toughness in dovetail joints, especially Style-B (longer dovetail tenon height), which, despite a smaller strength increase than Style-A (shorter dovetail tenon height), exhibits significant improvement in both aspects. However, Style-A's higher stiffness might concentrate loads in joint regions, requiring consideration for additional load management.

Failures predominantly start at the core adhesive and later propagate to the aluminum honeycomb, with core buckling and facesheet-core debonding observed at different load levels. While Style-A achieves higher load-carrying capacity, it comes at the expense of reduced toughness and ductility. Style-B's higher toughness due to increased shear deformation in the core is critical for damage tolerance but suggests potential for further improvement.

Manual processing limitations affected the dovetail joint quality, indicating potential performance enhancement with laser or automated cutting techniques. Addressing core distortion could reduce facesheet wrinkles and enhance overall performance. Future research should explore facesheet-core bond-line strength's role in fracture propagation and its interaction with various materials.

In essence, the study underscores the potential of dovetail joints in enhancing strength and toughness in composite structures. It identifies trade-offs between joint types and highlights the need for improved manufacturing methods to optimize performance while addressing structural vulnerabilities for practical applications.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF CORE SPLICING CONFIGURATIONS IN AN ADVANCED COMPOSITE SANDWICH STRUCTURAL SYSTEM

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ABSTRACT

In this study, an investigation is presented on the effects of the honeycomb core splice gaps on the performance of advanced composite sandwich structures consisting of aluminum honeycomb core and carbon-fiber/epoxy facesheets. The experimental and numerical investigation explores the effects of core thickness, facesheet thickness, splice gap width, and the presence of core splice adhesive on the structural response of the composite sandwich structure. The specimens fabricated with the splices exposed to primarily bending and shear to understand further how the core splice interacts with the overall structural response under such loading conditions. In addition, 3D finite element models investigated the failure modes in the specimens by examining the strain fields for core-spliced sections of the sandwich structure under the experimentally observed loading conditions. Various failure modes are observed in the experiments ranging from core shear failure, facesheet debonding, or fracture depending on the location of the core splice, core, and the facesheet properties. The results illustrate the importance of proper detailing and analysis of core splices in composite structures made from sandwich designs.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETECTION AND LOCALIZATION OF INTERNAL DAMAGE IN SEALED SPENT NUCLEAR FUEL CANISTERS USING A MULTI-TASK CONVOLUTIONAL NEURAL NETWORK (CNN)

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ABSTRACT

Spent nuclear fuel (SNF) assemblies (FAs) are comprised of bundled fuel rods that are highly radioactive. They must be stored in sealed stainless-steel canisters during interim storage periods to shield their radioactivity. During handling operations, transportation, or extreme events, the FAs inside the SNF canisters may become damaged. Therefore, assessing the structural integrity of FAs inside the canisters before long-term storage is crucial. Since the canisters are sealed, any non-destructive evaluation (NDE) measurements can only be taken on the exterior surface of the canister. Currently, the research is more concentrated on developing NDE methods for detecting cracks on the canister's surface with less emphasis on identifying internal damage specifically to the FAs. Therefore, this study bridges this gap by developing a multi-task convolutional neural network (CNN) to detect and localize the internal FA damage simultaneously. Experimental modal analysis was conducted on a 2/3-scale mock-up canister with accelerometers attached arbitrarily on the canister bottom plate. The differences between the frequency response functions (FRFs) of an intact fully loaded canister basket (FLCB) system and those of the canister with simulated internal damages were computed and used as input for the muti-task CNN. The network performed two classification tasks: one predicted FA damage levels and the other localized the damage to a specific quarter of the canister. The CNN combined the loss from each classification task into one final loss used for back-propagation during training. Research results demonstrate that the multi-task CNN exhibited exceptional performance on the testing dataset with a Macro-F1 score of 0.986 for the damage detection task and 0.957 for the localization task. Predictions generated for sensors located in the same quarter as the damage demonstrate a strong confidence that the damage was present within that specific quarter. Then, to introduce model uncertainty, dropout layers were applied to the fully connected layers of the CNN. By running the forward direction of the trained model 1,000 times during testing, estimates of the probability density functions (PDFs) for the predicted class probabilities were constructed and assessed for sensors located in various positions. These probabilistic results confirmed the accuracy of the CNN in predicting the correct level of FA damage and its location inside the canister. Therefore, this multi-task CNN method contributes to the novel NDE of SNF canisters and has potential applicability in inspecting actual SNF canisters in field applications.

BELIEF DEEP MARKOV MODELS FOR POMDP INFERENCE AND SOLUTIONS

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ABSTRACT

This work introduces a novel deep learning-based architecture, termed the Belief Deep Markov Model (Belief-DMM), able to provide efficient, model agnostic inference in complex Partially Observable Markov Decision Process (POMDP) problems. The POMDP framework allows modeling and solving decision-making problems under uncertainty, formulated as sequential decision-making tasks under prescribed or infinite horizons. Currently, existing solutions are hindered from lack of knowledge of the parameters of the POMDP model, which, if not known a priori, must be inferred. The latter is no small task, especially in complex, high-dimensional, partially-observable environments, for which existing methods based on exact computations (e.g., via Bayes' theorem) or sampling algorithms do not scale well and ground truth states are not available. Belief-DMMs originally extend deep Markov models into the partially observable decision-making framework and allow efficient belief inference entirely based on available data observations via variational inference methods. By exploiting neural networks, Belief-DMMs can infer and simulate non-linear relationships in the system dynamics and naturally scale to problems with high dimensionality and continuous variables (states, actions, and observations). In addition, neural network parameters can efficiently be dynamically updated based on data availability via stochastic gradient descent. Belief-DMMs can thus be used to infer a belief variable, uniquely enabling the derivation of POMDP solutions via model-free reinforcement learning over the belief space. Alternatively, the Belief-DMM can be notably used to propagate beliefs in time under general settings, for POMDP solutions based on model-based reinforcement learning. We assess the efficacy of the proposed methodology by evaluating the model-agnostic inference capability of Belief-DMMs in benchmark problems comprising both discrete and continuous variables.

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BIOINSPIRED DYNAMICS FOR SOFT ROBOTS APPLICATIONS

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ABSTRACT

Soft robotics has surfaced as an innovative realm aiming to cultivate robots featuring flexible structures proficient in executing diverse tasks within diverse surroundings. Imitating biological entities constitutes a foundational strategy in the creation of flexible robots equipped with adaptable mobility. Within this context, this study explores the mechanical principles underlying the peristaltic locomotion typically adopted by some animals, e.g. earthworms and caterpillars, with the objective of theoretically forecasting their movement and replicating it.

These animals manifest a sequential contraction and expansion of body segments, facilitating effective crawling locomotion, thanks to pivotal characteristics like synchronized muscle contractions and frictional anchors. These particular attributes can be mimicked and employed for applications such as endoscopy and drug delivery, thus allowing innovative medical micro-robots to attain locomotion resembling that of caterpillars, easing traversal through confined spaces and adapting to varied environments.

Within this framework, this research provides insights into the mechanical models of such organisms, seeking to accurately comprehend the intricate mechanisms governing their gait. To achieve this, the in vivo movement of larvae samples has been analysed on diverse substrates composed of different materials, in order to clarify the roles played by the anchoring of terminal prolegs and the contractions primarily involving abdominal subunits.

Starting from the studies found in the inherent literature, a discrete model with multiple degrees of freedom, incorporating springs arranged in series, is employed to trace back the locomotion of each body segment of the animal. Moreover, additional Winkler-like constraints and friction constitutive relations are imposed on specific subunits to regulate their interaction with the substrate and anticipate the detachment of certain prolegs/hairs of the caterpillar/earthworm. By triggering the dynamics through muscular contractions that are assumed to be the initial or the end part of the animal, the crawling gait of the larva has been investigated. Finally, based on the numerical values experimentally confirmed, several parametric analyses are conducted to comprehend the impact of the interplay between anchoring and muscular contractions on the overall behaviour of the system.

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Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BUCKLING IDENTIFICATION OF A PROFILED STEEL DECK THROUGH STRAIN MEASUREMENTS USING DISTRIBUTED FIBER OPTIC SENSING

Gowshikan Arulananthan[1], Nate Opperman[1], Hyeyoung Koh[1], Jesse Hampton[1] and Hannah Blum[1]*

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ABSTRACT

Distributed Fiber Optic Sensing (DFOS) is becoming a widely engaged technology in Structural Health Monitoring (SHM). This is due to its immanent advantages over conventional technologies like electric strain gauges such as insensitivity to electromagnetic disturbances, compact size, robustness, and capability for continuous measurements. Out of the three types of light backscattering used in DFOS, both Brillouin and Rayleigh are used in distributed temperature and strain measurements. While Brillouin-based Optical Time Domain Reflectometry (BOTDR) is ideal for monitoring large-scale structural and geotechnical applications [1] with a sensing range spanning in kilometers, the spatial resolution of such systems is on the order of meters (~ 1 m), making it difficult to monitor localized variations in strain and temperature. Techniques based on Rayleigh backscattering like Rayleigh Optical Frequency Domain Reflectometry (Rayleigh-OFDR) offer spatial resolution on the order of millimeters (up to 0.65 mm) but limiting the maximum sensing lengths to less than 100 m, therefore making it ideal for monitoring single structures. It was previously shown that Rayleigh-based DFOS can capture the points of inflection, support moment transfers, crack locations, and openings in concrete structures [2]. However, to identify how a Rayleigh-based OFDR system interprets the behavior of thin-walled steel deck prone to local and global buckling, a laboratory test was conducted on a two-span simply supported ASTM A653 Grade 80 1.5WR22 type steel deck in a vacuum box subjected to uniform pressure loading. Fiber optic cables were attached to several top and bottom flanges of the steel deck in the longitudinal direction. The steel deck was equipped with strain gauges near the fiber at selected locations to validate the strain measurements from the Rayleigh OFDR system. Strains were recorded as the pressure in the vacuum box was increased, causing the deck to deflect and experience local buckling. Initial interpretations of the test results show that the Rayleigh OFDR system could identify multi-scale strains including the global deformation of the deck as well as local buckling of the deck top flanges.

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Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN GURSON-TVERGAARD-NEEDLEMAN MODEL FOR DUCTILE FRACTURE

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ABSTRACT

The Gurson-Tvergaard-Needleman (GTN) model is a popular micromechanical model that is used to predict ductile fracture initiation in metallic components. However, using the GTN model for fracture prediction in large-scale simulations is computationally expensive. Uncoupled models are used as they are computationally inexpensive, but they cannot accommodate the micromechanical parameters that are accounted for by models like GTN and its variants. In this work, a data-driven uncoupled GTN model was developed for fracture initiation prediction and is validated on the ASTM A992 structural steel fracture data. A feedforward neural network (FNN) was trained using a dataset of 49,875 data points generated from representative volume element (RVE) simulations of ASTM A992 steel using the GTN model. The RVE simulations systematically varied 6 key input parameters: initial void volume fraction, void volume fraction at nucleation, effective plastic strain at nucleation, nucleation strain standard deviation, triaxiality, and void volume fraction at fracture. The configured 7-layer FNN with over 45,000 trainable parameters achieved a mean absolute error of 0.00143 and a relative error within 5% for over 99% of the data points. This computationally efficient data-driven model can accurately predict fracture initiation in ASTM A992 steel components. Moreover, the framework developed here could be extended to build similar uncoupled models for other computationally expensive constitutive models. This paradigm can enable practical damage analysis of large-scale structural steel systems and will be discussed in the talk.

ORIGAMI-WRAPPED THIN-SHELL STRUCTURES WITH CORRUGATED UNFOLDED FORMS: DESIGN, ANALYSIS, AND EXPERIMENTS

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ABSTRACT

“Flasher”-based origami wrapping patterns have been previously described and have shown to be useful for a variety of engineering applications [1]. At the 2019 EMI conference [2], one of the present authors described a class of thin-shell structures that can be compactly stowed using origami wrapping methods and that have a corrugated non-planar form when deployed. These structures cannot reach a flat state, by design, and the persistent corrugations provide out-of-plane bending stiffness much in excess of bending stiffness of a planar thin shell alone. Algorithmic design of the form of these corrugations guarantees that the structure can be unstrained both when compactly wrapped and when fully deployed.

Here, we review the design methods for such structures, and describe testing and analysis conducted since 2019 to demonstrate this bending stiffness, and structural finite element analyses conducted to capture these effects. This recent work is to appear in a journal publication [3]. Both the experimental and the numerical models demonstrate compact stowage while accommodating for material thickness through spiral wrapping, in addition to stiffness in the unfolded configuration. We show a reasonable match between the experimental results and the numerical results.

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Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEEP REINFORCEMENT LEARNING STRATEGIES FOR INERTER-INTEGRATED DEVICES WITH MECHANICAL MOTION RECTIFIER

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ABSTRACT

Various kinds of devices employing inerter technologies have been proposed for the purposes of structural control and energy harvesting. In these devices, generally, a damping element to absorb vibration energy is employed along with the inerter. In the conventional inerter mechanism, however, the velocity of the inerter is reduced to zero when the direction of vibration changes, resulting in a reduction in the energy absorption capability of the damping element. To address this issue, inerter-integrated devices that use a mechanical motion rectifier (MMR) to constrain the behavior of the inerter in one direction have been proposed. Although, like other structural control devices, the performance of these devices is expected to be improved by applying variable damping technologies, the MMR is a nonlinear mechanism, thus it is difficult to apply widely-used control algorithms developed for linear systems. Thus, in this research, deep reinforcement learning (DRL) strategies are applied to control the variable damping in the inerter-integrated devices with MMR. As a numerical example, a single-degree-of-freedom (SDOF) is considered, and the effectiveness and feasibility of the proposed control strategy by the DRL scheme are investigated.

UNCERTAINTY IN SILICATE MINERAL DISSOLUTION RATES AND ITS ROLE IN CONSTRAINING REACTION PATHS IN MGO-SIO2-H2O SYSTEM

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ABSTRACT

The evaluation of inherent uncertainty in dissolution rates of silicate minerals making earth’s upper mantle is essential in constraining geochemical reaction paths in MgO-SiO2-CaO-H2O-CO2 system that is associated with evolution of mineralogy, rheology and hydromechanical properties of ultramafic rocks. In particular, the rate of dissolution of Mg- and Ca-silicates plays an important role in (i) serpentinization of the peridotites at ocean spreading centers, and (ii) maintaining atmospheric carbon concentrations through interaction of CO2-bearing fluids with mafic and ultramafic rocks. In this study, a database of dissolution rates for two common minerals, olivine and pyroxene, is developed. The dissolution rates are interpreted using a simple model k = r (aH+n) within the framework of the Transition State Theory (TST) by assuming dissolution rate is linearly related to the aqueous proton (H+) activity aH+ at far-from-equilibrium conditions. The results are used to determine the uncertainty in parameter n. The implications of the uncertainty in n for constraining geochemical reaction path are discussed using activity-activity diagrams for the MgO-SiO2-H2O subsystem.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODE I FRACTURE LOAD PREDICTION OF COMPONENTS WEAKENED BY SYMMETRICAL AND ASYMMETRICAL V-NOTCHES USING THE PHASE-FIELD METHOD

Alireza Ashkpour[1], Jamal Bidadi[2], Hamed Saeidi Googarchin[2], Hsiao Wei Lee[1], Li Meng[1] and Ahmad Najafi[1]*

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ABSTRACT

This paper presents an investigation into the fracture analysis of the engineering components weakened by V-notches, utilizing phase-field method. In this regard, the study utilizes a combined experimental-numerical approach to assess the capability of the employed phase-field model to predict the fracture load of samples with different materials under mode I loading. In the first step, symmetrical V-notched Compact Tension (CT) samples made of epoxy resin were fabricated and experimentally tested to determine their corresponding fracture load and fracture path under mode I loading in different notch geometrical configurations (e.g., opening angle and notch-tip radius). The phase-field simulation results were further validated against the experimental literature results on graphite and polymethyl methacrylate (PMMA). A UEL subroutine was implemented in Abaqus software to solve the phase-field equations in a staggered manner [1]. For all the tested materials a reasonable consistency is observed between numerical and experimental fracture load; however, it is noteworthy that phase-field provided an even better estimation in case of the materials with more brittle fracture behavior.

In the second step, the study evaluates the effect of asymmetry in notch geometrical configurations on the strength variation of the components containing notches. This will rotate the notch's bisector line to the asymmetry angle, which transforms the pure mode I loading configuration to a mixed mode I/II loading. Mode mixity parameter (ϕ) is computed for each one of the assessed samples by utilizing the magnitude of stress ahead of the notch tip. Furthermore, the effect of opening angle and notch-tip radius were evaluated for sharp and blunt V-notches to determine the contribution of each parameter to the variation of the fracture load due to the existence of asymmetry. The study shows that the highest amount of strength reduction due to asymmetry relates to the sharp V-notch case. Also, it is found that the strength reduction occurs at the lesser amounts of asymmetry angle (e.g., 5 to 10 degrees) and after reaching a threshold no significant strength reduction is observed in the component.

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Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN END-TO-END FRAMEWORK FOR BUILDING INVENTORY GENERATION THROUGH PUBLIC DATA FUSION AND ARTIFICIAL INTELLIGENCE

Mohammad Askari[1], Mohammad Hesam Soleimani-Babakamali[1] and Ertugrul Taciroglu[1]*

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ABSTRACT

Comprehensive regional risk assessments are indispensable for determining areas susceptible to hazard exposure, laying the groundwork for effective risk mitigation strategies. It's essential to recognize that the type of hazard alone doesn't determine the impact; the specific characteristics of the infrastructure in question are equally crucial in how they interact with the hazard. These characteristics often vary based on the hazard type. While numerous datasets, especially in the United States, offer some insights into these factors, they fall short in terms of comprehensiveness and fail to cover all necessary attributes. No single dataset fully encapsulates all the attributes relevant to different hazards. However, these datasets still hold significant value and can be effectively integrated using Geographic Information Systems (GIS) data technology. Moreover, the incorporation of Artificial Intelligence (AI) plays a transformative role, either by filling data gaps or by generating new features not present in existing datasets. This includes missing information on building attributes, such as roof shape, roof pitch angle, number of openings, and the presence of a garage. Considering the specific requirements for analyzing hurricane hazards and the capabilities of existing simulation tools, we have developed an advanced, comprehensive framework. This framework assesses large geographic areas and provides a detailed building inventory. We have successfully applied this framework in North Carolina state, and in Houston and Port Arthur counties in Texas, showcasing its effectiveness in practical applications.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NONLINEAR SOLID MECHANICS WITH THE SHIFTED BOUNDARY METHOD

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ABSTRACT

We propose a new unfitted/immersed computational framework for nonlinear solid mechanics, which bypasses the complexities associated with the generation of CAD representations and subsequent body-fitted meshing. This approach allows to speedup the cycle of design and analysis in complex geometry and requires relatively simple computer graphics representations of the surface geometries to be simulated, such as the Standard Tessellation Language (STL format). Complex data structures and integration on cut elements are avoided by means of an approximate boundary representation and a modification (shifting) of the boundary conditions to maintain optimal accuracy. An extensive set of computational experiments in two and three dimensions is included.

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Small scale phenomena in sustainable & complex materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FROM SMALL SCALE FRACTURE TESTS TO OPEN METROLOGY & CIRCULAR ECONOMIES

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ABSTRACT

Characterization methods used for investigating the mechanics of materials and structures, from Da Vinci and Galileo to modern experimentalists, fall short for determining properties at small length scales. Moreover, such investigations become challenging for complex shapes, or under extreme environmental conditions. Athanasiou's lab is focusing on this exact issue, aiming to address complex social and environmental problems by introducing characterization methods that can enable the invention of advanced, high-performance materials and structures. In this talk, pioneering methods for mechanics investigation at small length scales, complex geometries and extreme conditions will be presented. The potential and applications of these methods will be discussed, highlighting how high-throughput, accurate, and reproducible characterization under challenging conditions can be used to create next-generation energy storage devices, and remove of emerging pollutants from soil and water.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

METAMODELING OF DYNAMIC NONLINEAR SYSTEMS BY PHYSICS-INFORMED LSTM NETWORKS AND TAYLOR SERIES EXPANSIONS

Haimiti Atila[1] and Seymour Spence[1]*

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ABSTRACT

In the performance evaluation of high-dimensional nonlinear and dynamic structural systems against extreme natural hazards, the incorporation of uncertainty is a challenging computational task. Many recent approaches have turned to neural networks as a metamodeling technique to address this challenge. However, several hurdles remain, including: 1) the substantial amount of training data required to achieve a desirable accuracy; 2) the need during training for the nonlinear force as an output in most physics-informed neural networks; and 3) the difficulty associated with predicting the response of systems are all degrees of freedom as opposed to a limited subset of responses. This study aims to introduce and validate a physics-informed Long Short-Term Memory (LSTM) framework capable of accurately modeling the time history response at all degrees of freedom of highly nonlinear dynamic structural systems using limited training data and without explicitly requiring nonlinear force outputs. Specifically, the high-dimensional system is transformed into a low-dimensional space using singular value decomposition. Subsequently, a novel physics-informed LSTM framework is used to learn the low-dimensional system. In particular, the dynamic equation of motion is leveraged to construct the physics loss of the LSTM. Velocity and acceleration are approximated through numerical differentiation while the nonlinear forces at each training iteration are estimated using a Taylor series approximation. The effectiveness of the framework is demonstrated through application to a full-scale 37-story steel moment-resisting frame subjected to seismic loads. The physics-informed LSTM exhibits high accuracy in simulating various responses of interest in the test dataset. Moreover, when compared to a pure data-driven LSTM, the proposed physics-informed LSTM achieves similar performance (measured by mean absolute error) using, however, 75% fewer training samples. This significant increase in efficiency highlights the strength of the proposed framework.

CURVATURE-MATCHING MECHANICS IN SKIN-BASED BIOELECTRONICS TO MINIMIZE INTERFACIAL STRESSES

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ABSTRACT

In this talk, we propose a geometrical and mechanical design strategy for stretchable electronics to improve wearability and comfort by reducing the magnitude of interfacial stresses and ensuring that the spatial stress distributions remain below the somatosensory threshold for skin sensitivity in bio-integrated medical applications. Conceptually, bioelectronic devices with soft polymeric encapsulations and internal rigid electronic components result in a mechanically hybrid composite structure, with intrinsically soft mechanics to facilitate integration with biological tissues through mechanical compliance. For accurate signal acquisition and sensing in curvilinear regions (e.g., limbs, chest, forehead), bioelectronic devices are pressed and bent to closely match the skin morphology, resulting in additional interfacial stresses. In the present work, we demonstrate how curvature-matching designs for the bioelectronic–skin interface can reduce the resulting normal and shear stresses generated from device adhesion and skin stretching during dynamic motions. Finite element modeling of the skin curvature, encapsulation, and internal electronic layouts was used to quantify the spatial distribution of the underlying stresses at the skin interface based on a mismatch curvature angle θ between the device and skin. The results show that curvature-matching designs for selected cases of $\theta = 30$ deg and 60 deg can reduce the normal and shear stresses by up to 45% and 70%, respectively, even for a stretch of up to $\lambda = 1.3$. The proposed curvature-matching design strategy can inform the future design of user-specific bioelectronics to create anatomically compatible geometrical layouts that enhance mechanical compliance and enable physiological monitoring and integration in curved biological structures.

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LINEAR REGRESSION ANALYSIS OF STEADY STATE WATER CONTENT IN MODIFIED COLUMN TESTS USING MACHINE LEARNING APPROACH

Zafar Avzalshoev[1] and Taro Uchimura[1]*

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ABSTRACT

The frequency of surface landslides has increased due to recent changes in meteorological patterns, which are marked by sudden, localized heavy precipitation. This has made advanced forecasting and early warning systems essential. This work is a logical progression of earlier investigations into the steady-state volumetric water content and its complex correlation with pore water pressure.

This study uses data from 17 modified column tests with columns 1 meter high and 10 cm in diameter. These tests cover a wide range of situations, such as drained and undrained scenarios, as well as surrogates for slopes with both absorbent and nonpermeable layers. Additionally, the tests cover a range of soil configuration densities, from loose to dense. Under these carefully regulated circumstances, we measured the volumetric water content and pore water pressure.

We create a predictive model for shallow landslides using knowledge gleaned from these model tests. Our method uses machine learning techniques to delve into the behavior of volumetric water content in a steady state. This predictive model is an affordable way to predict when slope failures will occur, especially in areas where the cost of installing costly monitoring sensors may be prohibitive.

The present work trains the entire model with data from the modified column tests. This means building feature tables, using sophisticated machine-learning techniques, and thoroughly refining the model. Our main goal is to combine the empirical data from physical model testing with machine learning capabilities. By integrating these two methods, we aim to raise the accuracy of models that predict shallow slope failure and deepen our understanding of soil behavior, particularly in quasi-saturation.

This research project is a significant step towards highly effective and affordable landslip prediction and mitigation techniques. Our objective is to contribute substantially to developing dependable early warning systems for slope instability by fusing empirical knowledge from experimental testing with the computational capacity of machine learning. These systems have the potential to drastically lower risks and vulnerabilities while revolutionizing safety measures in landslide-prone areas.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE MODEL OF FRESH ULTRA HIGH PERFORMANCE CONCRETE FOR THE SIMULATION OF 3D PRINTING: THE EFFECT OF THIXOTROPY

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ABSTRACT

Since the construction industry is increasingly using advanced materials and digital manufacturing techniques, incorporation of UHPC in 3D printing processes has become increasingly popular in recent years, due to its exceptional mechanical properties and potential for complex design geometries. However, the fresh state behavior, especially thixotropy, remains a critical aspect influencing the success of the printing process. Thixotropy, the time-dependent recovery of viscosity upon shear, introduces dynamic challenges in extrusion, deposition, and overall printability. This study presents a Discrete Element Model (DEM) developed for the simulation of fresh UHPC during 3D printing processes, with a particular focus on capturing the complex behavior of thixotropic properties. The proposed model is implemented in an open-source software called ProjectChrono. ProjectChrono offers a versatile and extensible framework for simulating multi-physics systems, including DEM-based simulations. The proposed model successively captures the interactions between individual particles to replicate a comprehensive framework for simulating their flow and rheological characteristics. The findings contribute valuable insights into optimizing the 3D printing parameters for UHPC, advancing the understanding of thixotropic effects in the context of additive manufacturing with high-performance concrete materials.

SYSTEM IDENTIFICATION OF RESPONSE OF OSCILLATING SURGE WAVE ENERGY CONVERTER USING PHYSICS-INFORMED NEURAL NETWORK

Mahmoud Ayyad[1], Lisheng Yang[2], Muhammad Hajj[1], Ahmed Shalaby[1], Alaa Ahmed[1], Jianuo Huang[2], Raju Datla[1] and Lei Zuo[2]*

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ABSTRACT

Geometry optimization and power takeoff (PTO) control of oscillating surge wave energy converters (OSWEC) require the prediction of hydrodynamic response by solving the fluid-structure interaction (FSI) problem. However, high-fidelity simulations can capture significant physical features of complex FSI problems, such simulations may not discern underlying phenomena that are usually interrelated in a complex manner, which makes it difficult to characterize the relevant causal mechanisms. Also, the computational resources required to implement high-fidelity simulations usually limit the number of configurations for design and optimization purposes or effective control strategies. Thus, effective reduced-order models can be used to predict the hydrodynamic responses in the early design stages. They are also required for implementation of PTO control.

In setting up the governing equation, the radiation force, which includes damping and added mass forces, is represented by a convolution integral of a causal impulse response function because radiating waves continue to exert a force on the WEC for an indefinite time. Because of this integral, a direct numerical solution is effectively impractical. One approach to deal with the wave radiation damping force is to approximate it by a state-space model. Other forces impacting the response include the buoyancy and nonlinear damping related to the oscillation of the OSWEC's flap. We implement a multi-step approach to identify the unknown coefficients of the governing equation. Data from quasi-static, free response and torque-forced experiments are used to respectively identify the stiffness, radiation damping, added mass, and nonlinear damping coefficients. The data sets were generated from experiments performed in the wave tank of the Davidson Laboratory at Stevens Institute of Technology. The stiffness coefficient was determined from quasi-static experiments. Physics-informed neural networks (PINN) can leverage deep neural networks capabilities to infer hidden/latent information of interest from scattered data in time and space. Thus, we used the PINN to identify the coefficients of a state-space model that represents the radiation damping from the free response data. The same approach was then applied to torque-forced response data to identify the added mass and nonlinear damping coefficients. Validation of the identified coefficients and representative model of the response is performed by comparing time series of the reduced order model with those of the wave tank experiments over a range of frequency excitations representative of ocean waves.

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY-AWARE SUB-SURFACE MATERIAL CHARACTERIZATION VIA BAYESIAN RADAR SIGNAL PROCESSING

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ABSTRACT

Precise assessment of sub-surface properties is pivotal for various applications such as subsurface surveys, precision agriculture, and wildfire risk assessments. This study proposes a Bayesian model-updating-based approach for radar waveform inversion to predict sub-surface properties, e.g., dielectric permittivity, electrical conductivity, and depths of the material layers. The proposed Bayesian-model updating approach yields a probabilistic prediction of the parameters that can provide uncertainty related to the predictions. The proposed approach was evaluated on real ground penetrating radar (GPR) scans collected through laboratory and field investigations encompassing a wide range of sub-surface properties. As an application example, we focus on the estimation of moisture content and depth of soil and overlaying organic material strata similar to that found on the forest floor. Laboratory investigations included variations in the moisture content, depth of the top layer, and fineness of the top layer material. Field investigations included field moisture prediction for a span of sixteen days. The predictions were then compared with measurements made in the field. The results from both laboratory and field investigations demonstrated that the predicted permittivity and moisture contents are consistent with in situ measurements by Time Domain Reflectometry and gravimetric analysis. Reasonably accurate depth predictions were also achieved for the top layer. Nevertheless, for cases involving top layer depth greater than 10 cm and high moisture levels, inconsistent predictions were observed that can be associated with the attenuation of the radar signals. However, the inconsistent predictions showed lower probability density and higher standard deviation, which indicate higher uncertainty related to the predictions. Hence, the uncertainty obtained by the proposed approach can be utilized to identify such inconsistent predictions. Sub-surface parameter estimation using the proposed approach can enable better decision-making for risk assessment across various applications.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIMULATING THE URBAN CANOPY'S IMPACT ON NATURAL COOLING

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ABSTRACT

Energy demand for building cooling plays a dual role as both a contributor to and a byproduct of rising global temperatures. This duality makes building cooling both a sustainability and resiliency challenge. One alternative to conventional active cooling is natural cooling, where wind and/or buoyant forces drive air through a building when the temperature outdoors is cooler than indoors. The indoor environment, coupled with building materials, then functions as a thermal battery that sustains lower indoor temperatures as external temperatures rise. This latent cooling effect can either augment or replace active cooling.

While the wind speed and temperature from nearby weather stations can indicate when natural cooling may be suitable, the local climate around any given building is very difficult to predict. In particular, the effect of the surrounding urban geometry on the local wind field is poorly understood. Our research aims to fill this knowledge gap by quantifying the surrounding urban canopy's effect on interior airflow.

We use large-eddy simulations (LESs) to simulate wind flow through an idealized urban canopy with several building interiors. These interiors include multiple window configurations, probing the efficacy of different ventilation strategies across the domain. By varying wind speed, wind direction, urban density, and indoor temperatures, we investigate how the surrounding urban layout impacts interior airflow. Preliminary findings underscore the significant role of the surrounding urban layout in generating distinct interior flow rates across buildings that are otherwise identical.

These simulations of an idealized urban layout provide an initial exploration of urban parameters which impact natural cooling. Subsequent research will simulate more realistic urban layouts, leveraging these results to train machine learning models. These models aim to predict the potential for natural cooling in buildings on a larger scale than LES simulations, offering scalable insights into the effectiveness of natural cooling in mitigating building energy consumption.

QUANTIFICATION OF INFRASTRUCTURE SYSTEMS FAILURE RISK USING COUPLED BAYESIAN NETWORK-SYSTEM DYNAMICS MODEL IN A PROBABILISTIC HAZARD ENVIRONMENT

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ABSTRACT

Infrastructure systems' safety is a challenging problem due to system components' complexity, dynamic and multiobjective operations, and multiple sources of operational uncertainties. Moreover, infrastructures are exposed to probabilistic hazard disruptions that may impact one or more system components with different failure scenarios, leading to various failure modes and subsequent overall system failure. The probabilistic hazard behavior and the uncertain system response increase the complexity of quantifying system failure risk. As such, this study develops a coupled Bayesian Network (BN)-System Dynamics (SD) model to quantify infrastructure system failure risk based on more realistic probabilistic dynamic system simulations. The developed model uses BN to link the hazard event to overall system failure using conditional probabilities, representing the uncertainties of system components and the possible system failure modes. Subsequently, SD provides a comprehensive dynamic simulation for the complex infrastructure system that can identify such conditional probabilities for each failure mode, considering the probabilistic hazard and system behavior. An existing hydropower infrastructure is adopted as a demonstration example to show the efficiency of the BN-SD model in quantifying system failure risk and developing more reliable risk assessment plans for infrastructure systems.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYBRID PHYSICS-DATA DRIVEN DIGITAL TWINNING OF A 6 MW OFFSHORE WIND TURBINE FOR ESTIMATION OF AERODYNAMIC STIFFNESS AND DAMPING

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[2]Northeastern University

ABSTRACT

The reliability assessment of offshore wind turbines is crucial for ensuring a trustworthy long-term investment in offshore wind energy. This goal can be achieved through continuous monitoring of campaigns to record the dynamic response of structural infrastructures and track their health and performance conditions and also by developing a digital twin – a virtual replica of the system- as an effective tool for characterizing and predicting the structure dynamics. Its development involves creating a virtual model that closely approximates the actual structure by matching the modal parameters of the model to those identified from the measured response data. Given the complex loading conditions, this can be a challenging task with unknown unmodeled physics and parameters to account for.

This study focuses on the development of a hybrid digital twin of a 6 MW offshore wind turbine, which combines both physics-based and data-driven models. The main objective is to model the complex dynamics resulting from varying environmental and operational conditions. Specifically, the model aims to account for the aerodynamic stiffening caused by gyroscopic effects, as well as the aerodynamic damping at high wind and rotor speed values. These effects will be accounted for by considering an additional stiffness and damper at the hub height in the digital twin of the structure. A long-short-term memory (LSTM) model will be used to predict the stiffness and damper properties according to the operational information (wind speed, rotor speed, power generation, yaw, and pitch angle) collected in the monitoring Supervisory Control and Data Acquisition (SCADA) system data. The predicted values will be compared from the prior estimation of the stiffness and damper obtained via a finite element model updating approach, and backpropagate through the LSTM network to adjust its weights. The final optimal prediction of the stiffness and damper at the hub will be used to correct the digital twin of the wind turbine and reliably predict the dynamic response of the turbine.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYPERELASTIC SYMBOLIC MODEL DISCOVERY GUIDED BY POLYCONVEX NEURAL ADDITIVE REPRESENTATION

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[1]Columbia University

ABSTRACT

Despite recent successes in designing neural network architectures to model hyperelastic materials accurately, they are less interpretable than classical symbolic models, especially in understanding how inputs like strain invariants contribute to the strain energy functional. Symbolic regression algorithms are free-form models that find symbolic mathematical representations comparable to classical hand-written models. However, their application in mechanics faces practical challenges. These include computational costs that escalate when the dimension of input features increases beyond one or when attempting to encode physics constraints in their search space—a critical aspect for certified engineering applications.

In this work, we introduce a new algorithm that leverages the advantageous properties of both approaches, enabled by insights from classical theories of continuum mechanics. We formulate a subclass of polyconvex hyperelastic material models in an additive manner using univariate bases for each strain invariant. Each univariate base is parameterized by a convex neural network, enabling scalable discovery of such additive representations. These univariate bases are then extracted by a fast and parallelizable symbolic regression algorithm to discover the final symbolic model. In addition to interpretability, the discovered symbolic model may require fewer arithmetic operations than its deep neural network counterparts at inference. This aspect is crucial for scaling large-scale simulations, where the constitutive responses at every integration point must be updated within each incremental time step.

We compare our proposed model discovery framework against other state-of-the-art alternatives to assess the robustness and efficiency of the training algorithms and examine the trade-off between interpretability, accuracy, and precision of the learned symbolic hyperelastic models obtained from different approaches. Our numerical results suggest that our approach extrapolates well outside the training data regime, owing to the precise incorporation of physics-based knowledge.

Advances in fluid-structure interaction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIBRO-ACOUSTIC ANALYSIS OF FOAM-COATED PLATES: MODELING AND A COMPARATIVE STUDY OF BIOT-ALLARD AND EQUIVALENT FLUID MODELS

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ABSTRACT

This work analyzes low-frequency vibro-acoustic responses of a foam-coated plate within an acoustic cavity through both numerical analyses based on finite element formulation and experimental investigations. Comparison is made between the modeling of the porous medium using a mixed Biot-Allard pressure-displacement formulation and equivalent fluid models of rigid and limp types. The Biot-Allard model, which considers the elasticity of the skeleton, is recommended in cases where a porous material is bonded to an elastic structure. This recommendation stems from the model's capability to account for the displacement of the solid phase in the porous layer caused by the overall displacement [1, 2]. Nevertheless, when dealing with large-scale finite element models, this formulation may demand considerable computational time. The equivalent fluid model with the "rigid frame" assumption posits that the solid phase remains motionless, whereas the "limp" model, which is suitable for materials that have a higher bulk modulus, assumes a zero stiffness for the solid phase while considering its inertial effects [3]. Limiting degrees of freedom in the porous layer to pressure as the sole nodal degree, these formulations effectively reduce the overall number of degrees of freedom in numerical poroelastic modeling compared to Biot models. The validity of each model is discussed in relation to the properties of the porous medium and the applied boundary conditions.

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Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL MODELING OF AREA-PRESERVING BIOMIMETIC MEMBRANES

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ABSTRACT

Area-preserving material surfaces, despite their prevalence in both biological and synthetic structures like biomimetic membranes, are often overlooked. Artificial bilayers enable a new class of compartmentalized, tissue-like materials, exemplified by the abundance of area-preserving membranes. Modeling area-preserving surface and bilayer interfaces pose significant challenges and limits our understanding of the overall properties of tissue-like materials. Here, due to the nanoscopic thickness of biomimetic membranes, the material surfaces are treated as zero-thickness membranes encasing a bulk, and they possess their own thermodynamic structures. The primary focus of this presentation is to propose a new two-field mixed surface element that weakly imposes the area-preservability of interfaces, in the context of surface-enhanced isogeometric finite element framework. The developed computational model is tested and validated by comparing its results with micromechanical experiments involving both single vesicles and bilayer-hydrogel hybrid droplets. Compression tests are performed on vesicles composed of commonly used lipids for tissue-like materials to generate force-displacement curves and displacement profiles. These data are compared with numerical models to iteratively determine the surface properties of each vesicle type. The validated computational model further explores the collective behavior of droplets and elucidates to what extent the area-preserving deformations of material surfaces influences the overall mechanical properties. The developed framework will establish the computational foundation that not only enhances our understanding of these complex materials but also pioneers new methods for designing and characterizing these tissue-like structures.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ML-BASED SEISMIC RESPONSE RECONSTRUCTION BY USING A DOWN-SAMPLED SURROGATE AUTOREGRESSIVE MODEL: DSAM

Ihsan E. Bal[1] and Eleni Smyrou[1]*

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ABSTRACT

Accurate prediction of nonlinear dynamic response of structures has gained interest in the recent years due to the increasing computational capabilities both in the hardware and in the software sides. Due to the complexities in creating numerical models accurately representing the real structures (high fidelity models), and due to the difficulties in running those models as well as the inherent uncertainties associated with the numerical representation of physical systems, render nonlinear time history analyses rather unfeasible in most cases. Meta models, surrogate models and similar approaches of "modeling a model" are thus studied extensively for obtaining the nonlinear dynamic results without actually running a full simulation. Such approaches pave the road for conducting large amount of simulations for addressing the epistemic uncertainties, for conducting predictive maintenance of complex systems and for prediction of damages on the spatially distributed systems in catastrophic events such as earthquakes. Common approaches in response prediction make use of the machine learning techniques specifically designed for time-varying data. A common problem in such approaches is that existing models are not designed for very high frequency data such as those often used in structural engineering practice. Furthermore, most of the popular methods, such as LSTM, are not easy to conceive for most users and thus providing explainable results is rather difficult. In order to address these problems stated above, a simple autoregression method is presented here. The method operates on a set of down-sampled data, since most structural engineering problems require maxima of the results instead of the entire response per few milli-seconds. Furthermore, the response of the structure from a previous step is used in predicting the response of the next state, building thus an autoregressive prediction sequence. The method, called "Down-sampled Surrogate Autoregressive Model: DSAM" is tested on reinforced concrete frames subjected to various earthquake records. It is also discussed how the proposed method can be used for other structures, especially those which are more suitable for down-sampling; for example, long-period structures such as rocking systems or tall buildings.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

USE OF DEEP LEARNING METHODS FOR STRUCTURAL CRACK DETECTION: LIMITATIONS AND ROOM FOR IMPROVEMENTS

Ihsan E. Bal[1] and Eleni Smyrou[1]*

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ABSTRACT

Inspection of existing structural stock is becoming more and more important for the authorities. A widespread and regular engineering inspection of the built environment is necessary not only from the safety perspective but also from the perspective of sustainability, where preserving an existing structure results way less carbon footprint than re-constructing one. Inspection of the entire built environment, however, is not a feasible task since the limited resources would not allow such an endeavour. Use of new technologies thus becomes handy. Deep learning-based crack detection methods, such as the one proposed by the authors (Dais et al., 2021) can be implemented for easing the process, and substantially decreasing the engineering hours required, resulting thus cheaper and more feasible applications. Dais et al. (2021) and similar deep learning models, however, have several drawbacks when applied to actual situations. The background noise causes several false-positives, the width of the crack is not easily monitored since the accuracy of the width monitoring depends on various parameters (Bal et al., 2021), and finally, the data for training such models is still scarce (Boerema, 2024).

This presentation will be about the efforts of the authors for improving the deep-learning model they had proposed a few years back with other colleagues. The direction for research in this field, and the possible promising solutions to the problems mentioned above will be presented.

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Boerema D.H. 2024. Towards enhancing AI-based crack segmentation for masonry surfaces through 3D data set synthesis, MSc Thesis, University of Groningen.

STRUCTURAL SAFETY USE CASE FOR AN OPEN AUTONOMOUS PROGRAMMABLE CLOUD PLATFORM

Ihsan E. Bal[1], Eleni Smyrou[1] and Mesut Bogac Kaya[1]*

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ABSTRACT

Structural Health Monitoring (SHM) is gaining more interest thanks to more accessible sensors, faster internet connection and better performing computers among other reasons. The existing SHM industry is mainly operating on centralized computing principles, where issues such as latency, cost and reliability in cases of catastrophic aftermath of events, such as large earthquakes, are not addressed. The high frequency data collection and the demanding levels of precision for synchronization of sensors are the main reasons why the SHM sector is slow in picking up the smart IoT solutions and edge computing. One another reason is the lack of open source, easy-to-access platforms where the SHM operations can be shifted from the centre to the edge.

In this presentation, the structural safety use case, one of the six use cases of the EU-funded OASEES project (OASEES, 2023), will be presented. The OASEES project will deliver a European, fully open-source, decentralized, and secure Swarm programmability framework for edge devices and leveraging various AI/ML accelerators (FPGAs, SNNs, Quantum) while supporting a privacy-preserving Object ID federation process. An earthquake monitoring and decision support system, previously based on centralized computing principles, is being modified using the OASEES platform (Chochliouros et al. 2023). Opportunities, challenges and future of seismic and structural health monitoring in terms of edge computing will be discussed in this presentation. Real use case examples will be presented where centralized computing faces difficulties in terms of cyber security at the client side, communication issues and other barriers.

OASEES (2023). Open autonomous programmable cloud apps & smart sensors, Horizon Europe Project Funded by EU, available at: https://oasees-project.eu, last accessed: 20.01.2024.

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Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETERMINATION OF A BUILDING DRAG COEFFICIENT FOR FLOW RESISTANCE IN COMPLEX URBAN FORMS

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ABSTRACT

Urbanization and climate change are contributing to severe flooding globally, necessitating more accurate and efficient modeling techniques. Porosity shallow water equations (SWEs) provide a simplified alternative to the high costs of computational fluid dynamics techniques which solve the full SWE, especially for applications in complex real-world urban areas. However, approaches to the treatment of sub-grid scale buildings for flow resistance remain limited and rudimentary, mostly adopting idealized forms or vegetation models as a representation of the urban landscape. By applying these approaches to more complex urban forms and modeling the resulting resistance forces, we can establish a connection between the changes in flow resistance caused by buildings and the representative building drag coefficient cDb. In this study, we adopt the integral porosity (IP) shallow water model [1] and a vegetative resistance modeling approach [2] to determine the flow behavior in complex urban forms of varying porosity and spatial distribution. By adopting a novel mean-flow theory for urban flooding which relates flood depth to urban attributes, we introduce a generalized formulation of cDb for urban forms. Our results demonstrate that cDb is affected by the compounding effects of blockage and sheltering, which can be explained by assuming pairs of obstructions/buildings. As the porosity of the urban form decreases, assuming similar spacing in the x- and y- directions, the effects of sheltering within the pairs overcome the effects of blockage at a critical porosity of 0.58. While different aspects of this study agree with previous laboratory and field results, the range of porosities and the scale studied here provide novel insight to the interactions between obstructions in complex systems and their effects on drag considerations.

[1] B. F. Sanders, J. E. Schubert, and H. A. Gallegos, Integral formulation of shallow-water equations with anisotropic porosity for urban flood modeling, Journal of Hydrology (2008).
[2] H. M. Nepf, Drag, turbulence, and diffusion in flow through emergent vegetation, Water Resources Research (1999).

WAVE PROPAGATION IN SCUTOID-BASED TOPOLOGICALLY INTERLOCKING MATERIAL SYSTEMS

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[1]Purdue University

ABSTRACT

Observations of wave propagation in systems of rows and beds of spheres have demonstrated novel wave propagation patterns and non-linear wave propagation conditions when impact loads are applied in the row axis or the bed plane. In Ballance and Siegmund (2023) the investigation of wave propagation along a row of tetrahedra also demonstrates non-linear wave propagation effects in combination with effects of the building block and assembly geometry. Here we investigate wave propagation in a planar and topologically interlocking packing of scutoids. Such a topologically interlocked material (TIM) system (where individual blocks cannot be removed without overall disassembly) can be subjected to transverse impact conditions. Our work employs an explicit finite element code (ABAQUS) with Individual building blocks that are fully 3D linear elastic bodies interacting with neighbors by contact and friction. We compute phase velocities, amplitude distributions, and wave patterns. We consider two scutoid configurations (pentagonal and hexagonal) and the canonical dense packing of tetrahedra in the plane for comparison. Both even-numbered and odd-numbered assemblies are considered. We report results in which we demonstrate wave propagation patterns in TIM systems which significantly depart from those observed for monolithic solids as well as for sphere assemblies. While in a monolithic system, there is a center symmetric condition of the wave field, such conditions are substantially absent in the TIM systems. Wave speeds are found to be substantially anisotropic. Wave patterns and wave speeds are related to the symmetry conditions in the TIM system architecture. Specifically, we demonstrate the effects of a chiral character of the TIM assembly on wave propagation.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BUCKLING BEHAVIOR OF FIBER-REINFORCED ELASTOMERIC ISOLATORS UNDER ELEVATED TEMPERATURES

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ABSTRACT

Fiber-reinforced elastomeric isolators (FREIs) are innovative and cost-effective base isolation systems. They are composed by bonding together multiple layers of elastomer and fiber fabric alternately. One of the major advantages of FREIs is its lower weight as compared to the conventional steel-reinforced elastomeric isolators. Being lightweight, the FREIs could be easily transported and installed at the construction site with minimal labor costs. Moreover, the FREIs could be utilized in both bonded or unbonded conditions, wherein the isolators are either fixedly attached to the structure by the means of external steel plates or just placed under the superstructure without any bonding, respectively. In unbonded applications, the weight of the isolators reduces further, thus enhancing its ease of implementation. However, one of the notable differences of the FREIs with the conventional steel-based isolators is its lower vertical load carrying capacity. Also, due to the flexibility of the fiber fabric reinforcing layers in the FREIs, the buckling behavior of the FREIs needs to be assessed cautiously. Although considerable studies have been conducted on the buckling of base isolators, including FREIs, their behavior under elevated temperatures is not well-explored. This is important because often after a major earthquake event, fire hazards could follow. Therefore, the integrity of the base isolation system under elevated temperatures is essential even when the isolators are only subjected to the vertical load from the superstructure. The failure of isolators under the self-weight of the structure could cause devastating effects on the base-isolated structure. Therefore, the objectives of the present study are to evaluate the buckling behavior of FREIs under elevated temperatures; and to obtain the influence of the inherent properties of the FREIs on their buckling performance under elevated temperatures. In this study, 3-dimensional (3D) finite element (FE) models of FREIs are developed and validated from literature. Nonlinear buckling analyses are conducted to obtain the buckling behavior of isolators at ambient and elevated temperatures, under pure compressive load. Further, the inherent properties of the FREIs are varied such as the shape of the isolator, shape factor of the isolator, and the aspect ratio of the isolator. Subsequently, the buckling load capacity of the various FREIs under elevated temperatures is evaluated. Results reveal that elevated temperatures could play a significant role in the buckling behavior of FREIs. Therefore, suitable considerations must be undertaken during the design of FREIs to make the base-isolated structures resistant to fire scenarios.

Keywords: base isolation, buckling, earthquake, fiber-reinforced elastomeric isolator, fire

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN UPDATING OF HIERARCHICAL MODELS APPLIED TO CALIBRATION AND UNCERTAINTY QUANTIFICATION OF CONSTITUTIVE MATERIAL MODELS

Maitreya Manoj Kurumbhati[1]*, Aakash Bangalore Satish**[2] *and Joel Pascal Conte*[1]

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ABSTRACT

The values of parameters of constitutive material models employed in finite element models are crucial to closely predict the actual structural response. Employing realistic cyclic material constitutive models calibrated to experimental data is essential for accurately predicting the nonlinear dynamic response of structural systems when subjected to extreme loads such as earthquakes.

This study focuses on the inference and uncertainty quantification of material model parameters from an experimental dataset comprising data from experiments conducted on multiple specimens of the same kind. Traditionally, Bayesian inference is performed either after pooling data from all specimens or considering data from a single specimen, which neglects the inherent variability among specimens of the same kind. While these methods quantify the estimation uncertainty in the material model parameter values, they do not characterize the uncertainty arising from specimen-to-specimen variability. Additionally, these traditional approaches struggle to accurately simulate the response of new specimens. To overcome these limitations, this study introduces a novel application of hierarchical Bayesian inference for calibrating material model parameters. Hierarchical Bayesian modeling quantifies both the epistemic uncertainty in estimating the parameters of the model and aleatory specimen-to-specimen variability.

In this study, the well-known Giuffré-Menegotto-Pinto (GMP) uniaxial material model for reinforcing steel is calibrated based on a dataset of experimental cyclic tests conducted on thirty-six steel specimens. These specimens originate from three different manufacturing mills, comply with two different manufacturing standards, and are subjected to different strain histories resembling those experienced during seismic events by reinforcing steel bars within reinforced concrete structures. Material model parameters are calibrated using both traditional and hierarchical Bayesian approaches, and the results are compared. Based on the experimental dataset used in this study, a joint probability distribution of the GMP material model parameters is provided. This distribution quantifies both epistemic (due to finite sample size) and aleatory (coupon-to-coupon) variability or uncertainty. It can be employed for uncertainty propagation in reliability and risk analyses of nonlinear dynamic systems.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL LATERAL TORSIONAL BUCKLING OF SIMPLY SUPPORTED ANISOTROPIC LAMINATED WEB BEAMS SUBJECTED TO A SINGLE MID-SPAN LOADING

Mohammad Bani Hani[1] and Hayder Rasheed[1]*

[1]*Kansas State University*

ABSTRACT

In this study, experimental investigations for lateral torsional buckling of laminated composite web-simply supported beams are presented. A total of eight glass-fiber reinforced polymer beams with varying l/h ratios and ply layups were experimentally tested for simply supported end conditions. The experimental response is compared against an analytical approach used to find the critical buckling load. Eigen value analysis was performed to benchmark the analytical buckling load using Abaqus. Furthermore, the Southwell technique was applied to extract the actual experimental buckling load from the experimental nonlinear response in cases where the tested beam behavior did not yield a fully buckled configuration. Various length/height ratios and ply layups of different anisotropic fiber orientations were comparatively examined.

A NUMERICAL COMPARISON OF DIFFERENT METHODS FOR ESTIMATING NON-STATIONARY FAILURE PROBABILITIES OF AGING STRUCTURES SUBJECT TO HURRICANE HAZARDS UNDER CHANGING CLIMATE CONDITIONS

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[2]CITRIS and the Banatao Institute

ABSTRACT

Changes in climatic patterns are expected to produce increases in hurricane risk. Significant research has been devoted to predicting the changes in hurricane intensities and their effects on the failure probability of structures. Commonly, the total failure probability for a structural system over its design life is calculated by assuming a Poisson distribution with constant failure rate (homogeneous Poisson process) given by the annual probability of exceeding a specified limit state. However, this assumption is no longer valid when the failure probability is time-dependent, as in cases in which the risk is controlled by nonstationary processes induced by climate change or structural aging. In this study, several options to overcome the limitation of the homogeneous Poisson process assumptions are compared for a benchmark structure subject to hurricane hazard. Both hazard nonstationarity and vulnerability nonstationarity are considered using simplified models. This study is a first step toward the selection of a method to account for climate change effects when calibrating wind maps and partial factors for structural design standards.

WILDFIRE FRAGILITY ASSESSMENT USING DAMAGE INSPECTION AND SATELLITE IMAGERY

Prakash Singh Badal[1] *and Michele Barbato**[12]

[1]*University of California, Davis*
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ABSTRACT

Climate change has resulted in a notable rise in extreme fire weather and wildfires globally, particularly across the western US. Increased construction in the wildland-urban interface (WUI) regions has exacerbated the destruction of buildings from wildfires. In California alone, an average annual direct loss of $9.9 billion due to structural damage from wildfires has been estimated between 2017 and 2021. The wildfire risk for the built environment depends on a complex interaction between vegetation, weather, and building characteristics. An accurate assessment of wildfire risk is crucial for science-based decision-making, e.g., for wildfire-resilient construction and effective preparedness. Wildfire fragility is an essential component of probabilistic risk assessment. The objective of the present study is to develop and illustrate a framework for wildfire fragility of light-frame wooden residential buildings assessment from empirically observed wildfire damage data.

In the present study, we develop a methodology to meaningfully combine multiple heterogeneous sources of wildfire damage data, such as Landsat thematic mapper (MTBS) severity maps, satellite imagery, and damage inspection (DINS) reports. Adopting a probabilistic approach, we investigate the effects of the distance of a building from burning vegetation and nearby structures. Three modes of building ignition—direct contact, radiant heat, and ember attack—are delineated using empirical data to estimate their respective contributions. Finally, the wildfire fragility curves for light-frame wooden residential buildings are developed using four distance definitions as measures of wildfire intensity. The wildfire fragility framework is illustrated for the Camp Fire (2018) and the Tubbs Fire (2017).

The present study demonstrates that the fragility assessment solely based on field inspection can be inaccurate, thus indicating the need to supplement the DINS database with satellite imagery-based building footprint information. The results indicate that conditioning the vegetation-to-structure and structure-to-structure distance on the non-radiant heat transfer is an effective intensity measure for wildfire fragility. Further, buildings with one or more outbuildings are found to be associated with significantly higher probabilities of destruction than those without outbuildings. The proposed wildfire fragility framework is a crucial component to enable probabilistic risk assessment of built infrastructure subject to wildfire hazard.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION WITH GRAPH NEURAL NETWORK ENABLED THRESHOLDING

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ABSTRACT

Topology optimization algorithms often employ a smooth density function to implicitly represent geometries in a Cartesian grid. While this treatment offers great flexibility to parametrize the optimized geometry, this implicit representation often leads to a finite-size transition region within which the space is neither empty nor fully occupied. Since this transition region is fictitious, a post-processing is necessary to convert the density function into binary domain such that the learned geometry can be manufactured. While techniques, such as Solid Isotropic Material Penalty (SIMP) method, modify the objective function to facilitate convergence towards integer density values, the convergence and the final solution rely on the chosen penalty value. In this work, a Graph Neural Network (GNN) that works as a local filter to the design domain is used to leverage initial iterations of the SIMP method to predict a near-optimal topology. By incorporating the GNN model multiple times throughout the optimization process, the optimizer is guided toward a physical solution leading to accelerated convergence. This model considers only the local interactions among the finite elements within the design domain, making it suitable for every discretization and applicable to both 2D and 3D cases.

Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMIZING SENSOR PLACEMENT FOR CHARACTERIZATION AND CONTROL OF A METER-SCALE ORIGAMI PILL-BUG STRUCTURE

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ABSTRACT

In the field of structural engineering, the pursuit of innovative and sustainable solutions has given rise to a growing demand for adaptive structures capable of responding to dynamic environmental conditions. Venturing beyond traditional influences, the ancient art of origami has emerged as a powerful source of inspiration. Beyond its traditional artistic roots, origami's potential to inspire deployable structures has garnered attention in engineering circles. The strategic incorporation of biomimetics further amplifies the transformative possibilities, paving the way for adaptive structures that optimize both efficiency and functionality.

Amidst this exploration, the concepts of structural control and health monitoring become pivotal. Integrating these elements into the study, we delve into the deployment dynamics of a meter-scale origami pill bug (OPB) structure, a novel design inspired by the morphological characteristics of pill bugs. Monitoring the development of strain within the structure during deployment is crucial for understanding its behavior. To achieve this, strain gauges and load sensors are employed. This prompted the development of a sensor placement optimization algorithm to ensure efficient and holistic data collection with a limited number of sensors.

To identify critical areas within the structure, an analytical study using the dynamic relaxation method [1] is conducted. The results from this analytical study will inform the experimental setup by prioritizing the placement of strain gauges to these critical locations. The optimized placement of the strain gauges will ensure effective and efficient data collection. Additionally, insights gained from this research can provide valuable information on control strategies for the structure [2]. The synergy of analytical and experimental approaches contributes to a comprehensive understanding of the deployment dynamics of the OPB structure. Beyond its immediate applications, this research presents the potential for advancements in the design and control strategies of origami-enabled structures in civil engineering, underscoring its significance in pushing the boundaries of structural innovation.

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Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TRANSFER LEARNING-BASED MODEL FOR THE SERVICE LIFE PREDICTION OF FAÇADE MATERIALS

Felipe Basquiroto de Souza[1], Anthoni Giam[1], Yijie Chen[1], Sida Wu[1], Jiaqi He[1] and Sze Dai Pang[1]*

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ABSTRACT

According to the projections of various global climate models, the planet is due to face changes in climate within the coming decades. These climate changes are anticipated to directly impact the durability of façade materials, as they provide buildings with the first layer of protection against the weather. Specifically for cement-based façade materials (e.g., adhesive mortars, renders), an increase in air temperature combined with variations in rainfall values can make them more susceptible to cracking due to more extreme thermal shocks and wetting-drying cycles – significantly reducing their service life. In this context, improving our understanding of façade deterioration processes and predicting their service life is critical to preventing façade failures, improving public safety, and enabling the adoption of timely inspection regimes. However, current approaches for collecting the necessary data for service-life predictions (e.g., field testing, accelerated weathering testing) are costly, labor-intensive, and time-consuming. In collaboration with Singaporean building agencies, we introduce a transfer learning-based approach to address limited experimental datasets and model the mechanical behavior and service life of façade materials under different climate change factors. In this presentation, we focus on tiled-walled systems, which from a mechanistic point of view are among the most complex of the façade materials (e.g., thermal discrepancies between tile, adhesive, and substrate elements as well as susceptibility to moisture). To model the tiled-walled systems, first, in situ mechanical tests in various building façades across Singapore and accelerated weathering experiments were carried out. Then, a FEM model was built and calibrated based on transient mass diffusion analysis, and thousands of data points were generated to capture the influence of temperature, precipitation, and moisture on the mechanical properties of the system. Finally, we demonstrated the application of transfer learning to realize the service life predictions. More specifically, an artificial neural network model was first pre-trained in the large dataset (>30,000) obtained via the FEM simulations. Then, the pre-trained knowledge was leveraged to analyze the scarce experimental weathering data (tens of data points). It was found that the transfer learning-based model effectively captured the complex degradation behavior of tiled-walled systems, leading to more accurate service life predictions compared to other probabilistic models. The reported analyses provide a novel framework for designing more robust façade systems and inspection/maintenance regimes in preparedness for upcoming climate changes.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE PHYSIO-CHEMICAL CHARACTERIZATION OF MULTI-BINDER ECO-ULTRA-HIGH-PERFORMANCE CONCRETE (E-UHPC)

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ABSTRACT

A sustainable design approach towards eco-UHPC with reduced cement content involves increasing the volume of supplementary cementitious materials leveraging particle packing models. However, such multi-binder UHPC incorporates complex chemical interactions that impair the superplasticizer efficiency and overall rheological and mechanical performance. The underlying mechanisms and relative contribution of physical and chemical interaction on strength and rheological aspects are still not clear and require further investigation. Here, we studied five multi-binder UHPC with varying packing factors (32.9 to 46.0) with up to 55% SCM content. Our research shows that in high SCM systems restrained by water, physical packing predominantly governs early-age strength. Nevertheless, the rheological characteristics are multi-faceted and influenced by chemical interactions specific to mix compositions. We introduce the “fluidizing effect” to describe the superplasticizer sensitivity to mix composition, with packing playing a secondary role to account for the observed mechanical and rheological behavior. This study underscores the significance of optimizing the complementary role of granular packing, water demand, and chemical interaction to ensure eco-friendly UHPC with robust strength (118 MPa), low porosity (~3.0%), and self-consolidating properties (flow> 230mm). Notably, we mark the possibility of reducing the binder coefficient by three times (5.99kg/m3/MPa) even at 55% SCM content while maintaining adequate performance and emphasizing the potential of optimized multi-binder UHPC systems for sustainable construction.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SPRESS-SPRAIN CRACK BAND MODEL BASED ON LAGRANGE MULTIPLIER CONSTRAINT AND ITS VERIFICATION BY GAP TEST

Zdenek Bazant[1], Houlin Xu[1], Anh Nguyen[1] and Karel Matouš[2]*

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ABSTRACT

Preceding studies showed that the resistance of a heterogeneous material to the displacement field curvature is the physically most realistic localization limiter for softening damage and fracture. The curvature was characterized by the second gradient of the displacement vector field, which differs from the strain gradient tensor by the material rotation gradient tensor, and was named the 'sprain' tensor, whose work-conjugate force variable was called the 'spress' tensor. In the preceding work, the partial derivatives of the associated sprain energy density were used to obtain self-equilibrated sets of curvature-resisting nodal sprain forces, some of which had to be applied on nodes adjacent to the finite element. But his led to enormous computational burden. This burden is eliminated by formulating a finite element with linear shape functions for both the displacement vector and the approximate displacement gradient tensor. The derivatives of the latter then yield the tensor of displacement curvature (or hessian), obviating the need for adjacent sprain forces. The main idea is to use a Lagrange multiplier tensor to constrain the approximate gradients to the actual displacement gradients. A user element for Abaqus is formulated and used to demonstrate mesh-independent crack band growth, capturing the band width variation and smooth damage distribution across the crack band. The spress-sprain energy dissipation is shown to match various distinctive fracture tests of concrete, including the gap test and its simulation by the LDPM (discrete particle) model. Generalization to plastic-hardening metals (e.g., aluminum), which requires distinguishing energy dissipations at the micrometer scale crack front and in the wake of a millimeter scale hardening yielding zone, critical comparisons with peridynamics and phase-field models, application to deep sequestration of CO2 in peridotite are briefly mentioned in closing. Sponsors: NSF and DoE/EFRC.

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Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TAYLOR-SERIES EXPANSION FOR MESHFREE METHODS: SOLIDS AND SHELLS

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ABSTRACT

Numerical quadrature based on Taylor-series expansion approaches was introduced in the mid-80s for FEM to develop a parameter-free approach for hourglass control. It laid dormant for a while, and, much later, in the mid 2010s, it resurfaced in the context of RKPM to develop a so-called Natural Stabilization approach, which is arguably the most important recent breakthrough in RKPM that brought the necessary added robustness for a wide range of nonlinear solid mechanics applications. In this talk, I will present a general framework of Taylor-expansion-based methods in computational solid mechanics and its broad applicability to meshfree methods and beyond. I will demonstrate: i. How to develop Taylor-series-expansion-based formulations that are accurate and stable for nearly incompressible deformations; ii. How to stabilize correspondence-based Peridynamics without resorting to costly bond-associated approaches; and iii. How to develop general-purpose large-deformation meshfree thin shells.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCED CONCRETE SEISMIC CRACK PATTERN PREDICTION USING CONDITIONAL DIFFUSION MODELS

Reza Bazrgary[1] and Vedhus Hoskere[1]*

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ABSTRACT

In the aftermath of earthquakes, evaluating structural damage quickly and accurately is vital for safety assessments and effective recovery planning. Predicting expected crack patterns in structural components accurately can enhance these evaluations by supplying a vast amount of synthetic data for model training, which can then be used to infer the structural condition. However, due to the costly nature of non-linear simulations, traditional methods like finite element analysis are often time-consuming. Our study introduces a novel method using a conditional diffusion model that predicts post-disaster images of structural components. This method directly employs experimental data of shear walls with various structural design features like size, material properties, and loading conditions. Moreover, by integrating machine learning techniques with structural engineering principles, this approach significantly reduces the time and computational resources required, enabling rapid and reliable damage assessment in post-earthquake scenarios.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EQUITY-BASED RETROFIT DECISION-MAKING FOR GALVESTON'S ELECTRIC DISTRIBUTION NETWORK

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ABSTRACT

To improve community resilience, infrastructure can be retrofitted to enhance its performance against hazards. Due to resource limitations, organizations servicing communities must strategically target certain components for improvement. Priority for infrastructure retrofit decision-making has often been governed by system performance and derived metrics. However, after natural hazards populations of greater social vulnerability are often disproportionally impacted by service outages and are often serviced by more fragile infrastructure which can further exacerbate the post-event outage impact inequity. This service inequity hinders community resilience gains. To that end, an equity-based metric can be implemented to enable service equity considerations in retrofit decision-making alongside classic system performance metrics. The proposed metric is based upon Theil's T (Theil, 1967) which captures inequities in service provision among populations varying in social vulnerability attributes. The metric translates individual infrastructure components' quality to a system-level aggregate equity assessment.

This presentation will introduce the metric and its application to an Electric Distribution Network (EDN) relative to a hurricane hazard. Further, the metric will be implemented for retrofit decision-making in Galveston, TX to demonstrate the degrees of equity gains across various percentages of retrofit across the entire infrastructure stock. Additionally, since infrastructure quality information is not available for Galveston nor readily available for other locations, the demonstration will be conducted for multiple infrastructure quality assignments to demonstrate how equity-based decisions are impacted by quality characterization.

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Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INELASTIC BUCKLING AND ULTIMATE CAPACITY OF CRUCIFORM COLUMNS: RECENT ADVANCES

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ABSTRACT

From a stability perspective, the inelastic cruciform column presents a double challenge. The determination of the inelastic buckling stress constitutes a textbook example of the ‘plastic buckling paradox’, which leads to the untenable conclusion that torsional buckling is unaffected by the gradual loss of stiffness due to yielding. On the other hand, predicting the post-buckling behaviour and the eventual ultimate capacity of the cruciform column requires (currently non-existing) solutions to the Föppl-von Karman equations, which appear to be of prohibitive complexity.

The presented research expounds on recent achievements in surmounting both challenges. The plastic buckling paradox is circumvented by considering the cross-sectional stress resultants in a coordinate system attached to the deformed structure, which upon buckling gains an inclination relative to the principal directions of plastic flow. The latter initially remain unaltered during buckling, giving rise to plastic contributions to the shear deformations.

In a second step, approximate yet highly accurate solutions are constructed to the Föppl-von Karman equations for outstand plate elements. The original set of two coupled non-linear partial differential equations is thereby simplified into a single non-linear ordinary differential equation by employing the Vlasov assumptions of zero membrane shear and zero transverse membrane stresses. A solution is then obtained through a polynomial approximation. Geometric imperfections and residual stresses can be accounted for by the inclusion of equivalent imperfection terms in the equation. Additionally, a failure criterion is introduced, inspired by von Karman’s effective width concept, which limits the maximum longitudinal membrane stress to the yield stress. The result is a closed form equation for the torsional buckling strength of the cruciform column, which is a function only of the traditionally defined plate slenderness and a specific imperfection factor. This imperfection factor reveals the dependencies of the column capacity on the relative magnitude of the geometric imperfection as well as the material properties.

The new predictions of the buckling stress and ultimate capacity of cruciform columns were compared to previously published experimental data pertaining to AA6082 aluminium columns [1], and excellent agreement was obtained.

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Tropical cyclone induced winds, surge-wave, flooding and impacts on infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VALIDATING MULTIPHASE NUMERICAL SIMULATION OF SHOALING REGULAR AND IRREGULAR WAVES

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ABSTRACT

North American building codes currently evaluate the potential damage to structures from extreme weather hazards using inherently decoupled methods (ASCE-7-22), which may not account for realistic multiphysics loading such as coupling between high winds and storm surge with waves beneath elevated buildings during hurricanes. The potential discrepancy between a coupled and decoupled analysis approach is not yet well understood; fully-coupled studies have historically been limited in experiment due to flow similitude parameter scaling challenges (Reynolds number and Froude number scale incompatibly as test structure geometry is scaled), and limited in simulation due to novelty of the numerical methods. The long-term aim of this work is to build towards a validated, multiphase numerical framework capable of representing realistic multiphysics hurricane loading on buildings with quantified uncertainty and well-understood sensitivities.

As a first step towards this long-term goal, the current work validates Large Eddy Simulations (LESs) of large regular and irregular waves in still air propagating over a sloped near-shore bathymetry using experimental data collected at the OSU Large Wave Flume (Lomonaco et. al., 2019). The performance and numerical sensitivities (grid resolution, mesh quality, maximum CFL) of two Volume-of-Fluid multiphase solvers, OpenFOAM and charLES, are compared. Other potential sources of model form uncertainty are examined, including the LES subgrid scale model, turbulent wall function, interface capturing scheme, and wave generation/absorption method. The quantities of interest include mean water elevation and velocity statistics, period-averaged profiles for regular waves, spectra for irregular waves, and preliminary analysis of the impacts of various model parameters on the air phase. Future work aims to expand this validation to near-shore wind-wave interaction.

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Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ANALYTICAL MODEL FOR HYGROSCOPIC BILAYERS BASED ON SURFACE POROMECHANICS THEORY

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ABSTRACT

Hygroscopic actuators, mimicking many plant organs (e.g., pinecone scales, Chiral seed pods) that respond to moisture change with shape morphing and motion, are increasingly popular in soft robotics, responsive architecture, and artificial muscles. Hygroscopic bilayers made of a passive substrate adhered to an adsorptive porous coating can convert chemical potential differences of the adsorbate species present in the surrounding environment and within the pore space into mechanical energy through deformation and curvature development. These mechanical responses are driven by the adsorption-induced deformation of the active porous layer. As the partial pressure of adsorbate vapor increases, the surface stress along the pore wall changes, producing a strain isotherm that can exhibit intricate nonlinear and non-monotonic characteristics depending on the pore structure and the magnitude of the deformation. In this contribution, surface poromechanics (Zhang, 2018) and bilayer beam theory (Clyne, 1995), and Castigliano's second theorem for displacements are integrated to analytically model the adsorption-induced bending and reaction force of hygroscopic bilayers. Two types of bilayers with microporous and mesoporous coating are considered, and new adsorption isotherms are introduced and calibrated for each case. The deformation of the actuators at different humidity levels and the effects of the elastic property of the substrate, porosity, and pore size of the coating on the response of the actuator are discussed. The model performed very well for microporous bilayer where the material swells monotonically with increasing relative humidity. However, the current framework cannot depict the sudden shrinking of mesoporous materials at intermediate-high vapor pressure levels induced by capillary condensation. In addressing this, we proposed a unified surface poromechanics formulation to fundamentally incorporate the dynamic evolution of interfaces among the solid, the liquid, and the gas phases. The new formulation considers the physics of pore fluid phase changes between vapor and liquid phases, recovers the water retention characteristics curve for an unsaturated porous media, and captures the early Bangham swelling and the midrange contraction. In the limit cases with zero and 100% degree of saturation, we show the new framework degenerates to Biot's theory for biphasic porous medium.

Keywords: hygroscopic, bilayer, adsorption, poromechanics, porous media, capillary condensation

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETERMINATION OF PROBABILISTIC POWER SPECTRAL DENSITY PARAMETERS BY A DATA-DRIVEN AND PHYSICS-BASED APPROACH TO ESTIMATE FAILURE PROBABILITES

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ABSTRACT

The task of estimating failure probabilities in stochastic dynamics for existing buildings or in the design phase of new buildings is of paramount importance. Specifically in the presence of uncertainties in real data records and the PSD estimation process, accurate load models accounting for these uncertainties are required. Often the power spectral density function can be employed for this purpose as it determines the frequency content and amplitude of a stochastic process in time domain. Performing this analysis, insights about critical frequencies can be found. Therefore, a probabilistic PSD load model is inferred, which merges data-driven techniques with physics-based modeling approaches in order to derive a probabilistic set of PSD parameters of a known model, such as the Clough-Penzien PSD model. The approach is demonstrated by using artificial data, addressing challenges associated with estimating PSD functions from actual data. The proposed method is showcased through case studies, illustrating its capability to provide a robust assessment of structural reliability while considering uncertainties.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INNOVATIVE APPROACHES IN MODELING CORROSION-INDUCED DEGRADATION OF STEEL STRUCTURES: A MACHINE LEARNING PERSPECTIVE

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[1]Oslo Metropolitan University
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ABSTRACT

Corrosion-induced degradation poses a significant challenge to the structural integrity of steel components in various engineering applications. This paper presents recent advancements in the modeling of corrosion-induced degradation in steel structures through the application of cutting-edge machine learning techniques. The study focuses on leveraging the capabilities of machine learning to enhance the accuracy and efficiency of degradation modeling, offering a more comprehensive understanding of structural deterioration over time. The proposed methodology employs a combination of sensor data, environmental parameters, and historical corrosion records to train machine learning algorithms, facilitating the development of predictive models for corrosion-induced degradation. Various machine learning techniques, including support vector machines, neural networks, and ensemble methods, are explored to capture complex and non-linear relationships inherent in the corrosion process. The evaluation of the proposed models involves a comparison with traditional degradation modeling approaches, assessing the accuracy and reliability of predictions using various comparative metrics. By harnessing the power of machine learning, the study aims to provide a robust framework for predicting the progression of corrosion-induced degradation in steel structures, offering insights into potential failure modes and enabling proactive maintenance strategies. This will pave the way for more resilient and sustainable infrastructure through the integration of advanced machine learning techniques.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHEMO-MECHANICAL DESCRIPTION OF LIPID MEMBRANE HETEROGENEITY

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ABSTRACT

Plasma membranes are fundamental to drive many biological mechanisms connected to cellular homeostasis and metabolism as well as to adverse processes such as phenotype mutation and infection [1]. Such membrane-mediated phenomena occur by means of conformational changes (due to lipid order transitions occurring at lower scales) and the micro-mechanical interplay of lipids with transmembrane protein species, as well as molecular diffusion [3]. In fact, it is now confirmed that cell membranes are highly dynamical and heterogeneous systems experiencing a strong coupling between biochemical events and structural re-organization [4, 5]. In particular, they are characterized by fluid deformable surfaces expressing solid-liquid-like behaviors in a system where in-plane fluidity and elasticity may simultaneously emerge [6]. Therefore, a full multiphysics coupling is necessary to better understand the interactions between the kinetics of phase transition and the mechanical work performed by the activity of the transmembrane proteins on the surrounding lipids, that are in turn mediated by the membrane elasticity [7] and fluidity. Through these complex interspecific dynamics, signaling potential and intra-cellular processes result to be effectively affected by the competition between membrane stress and chemical potentials, that determine different morphological re-arrangements, alteration in diffusive walkways and coalescence phenomena. Therefore, our purpose is to investigate the dynamic visco-elastic response of plasma membranes to chemo-mechanical stimulus by using in-silico numerical simulations. In this way to effectively observe how the solid-fluid behavior of the bilayer evolves with membrane activity, being it influenced by the dynamics of the active embedded proteins and their interaction with the surroundings. This could have a potential impact on the possibility of testing/designing new or existing drugs by selectively control cellular mechanical properties.

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Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDRESSING CHALLENGES AND UNCERTAINTY IN THE TRANSITION TO ELECTRIC FREIGHT TRANSPORTATION: AN OPTIMIZATION-SIMULATION APPROACH

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ABSTRACT

The integration of battery-electric trucks (BETs) into land freight logistics, driven by the introduction of zero-emission zones, faces significant challenges stemming from an inadequate understanding of essential infrastructure requirements and constraints. The transition combines uncertainties from existing operations with the new requirements from emerging technologies. Specifically, addressing how existing operations planned for internal combustion engine (ICE) trucks, peak power limitations at charging sites, and their relation to charging infrastructure sizing poses new interconnected challenges.

To address these challenges, this paper presents an optimization-simulation framework designed to stress test and design private BET charging infrastructure under uncertainty. Initially, a mixed integer-linear program (MILP) is developed and optimized by leveraging existing scheduled itineraries. This process co-designs infrastructure and charging schedules in alignment with predetermined itineraries, aiming to minimize disruptions to existing operations while strategically accommodating charging requirements. Subsequently, the solutions obtained from the initial optimization are refined using an agent-based model. This model simulates the behaviors and interactions of vehicles and the charging network, providing comprehensive probabilistic outcomes for key operational metrics such as charging waiting times, anticipated peak power usage, and potential delivery failures.

We compare the performance of rule-based design and charging with our optimization approach, finding that the optimization of charging schedules yields the most relevant reduction in peak power usage, and active control of charging plays the most crucial role in reducing operational failures.

Our study underscores the role of optimization in resource-constrained scenarios, showcasing its effectiveness in reducing peak power usage and meeting operational requirements. Additionally, it highlights the use of agent-based simulations to propagate and quantify uncertainties while offering actionable insights to decision-makers. This approach promises practical applicability and potential integration in developing digital twins for planning and controlling the transition to sustainable logistics.

PERFORMANCE-BASED WIND DESIGN OF TALL MASS TIMBER BUILDINGS WITH ROCKING POST-TENSIONED CROSS LAMINATED TIMBER SHEAR WALLS

Nahom K Berile[1] and Matiyas A Bezabeh[1]*

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ABSTRACT

The current code-based wind design approach for main wind force resisting systems (MWFRS) equates the first significant yield with a structural failure. The limitation to linear-elastic capacity of members is primarily due to the mean component of wind loads in the along-wind direction extending for long durations, which can result in the accumulation of damage in structures. However, as we move towards performance-based approaches, controlled nonlinear-inelastic deformation in specially designed and detailed parts of MWFRSs can be allowed. Recent studies have shown that combining self-centering structural systems and performance-based wind design (PBWD) can limit damage accumulation and result in economic and safe structures. Coupled post-tensioned cross laminated timber (PT-CLT) walls are resilient lateral load resisting systems due to their ability to recenter and dissipate energy under controlled rocking. PT-CLT walls utilize post-tensioning tendons and coupling U-shaped flexural plates (UFPs) for recentering and energy dissipation, respectively. Analytical and experimental studies have demonstrated the effectiveness of these walls as main seismic force resisting systems in mass timber buildings. However, the use of PT-CLT shear walls as main wind force resisting systems (MWFRSs) in tall mass timber buildings has not been explored. Therefore, this paper develops a new PBWD approach for tall mass timber buildings with coupled rocking PT-CLT shear walls. The approach sets performance objectives corresponding to the decompression limit, effective linear limit, yielding of UFPs, yielding of CLT, crushing of CLT, and yielding of PT strands with a corresponding performance criteria. The proposed method is used to design 8-, 12- and 24-story prototype rocking mass timber buildings with PT-CLT shear walls. Three-dimensional multi-spring-based numerical models are developed in OpenSeesPy and calibrated based on component- and system-level experiments, as well as full-scale shaking table tests. A wind tunnel test dataset is used to define wind loads and perform nonlinear time history analyses under simultaneous along-, across, torsional-wind loads. Component-level responses are extracted and assessed considering the criteria for force- and deformation-controlled elements, while global responses are checked against drift limits. The performance of the buildings shows that PT-CLT walls can be utilized as MWFRSs in tall mass timber buildings with controlled rocking under wind load.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ECONOMIC LOSS ESTIMATION DUE TO HAZARDS DRIVEN BY CLIMATE CHANGE USING NON-STATIONARY MODELS

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ABSTRACT

In the face of climate change, the simulations on global climate models have indicated a gradual intensification of environmental hazards like thunderstorms, landslides, and atmospheric river landfalls, both in frequency of occurrence and magnitude. The prevalent literature on non-stationary modelling of hazards has amply shown that these hazards can be modelled as Marked Non-Homogeneous Poisson processes (NHPPs), in which the rate function that models the rate of hazard-occurrence, is considered to be time-dependent. The other crucial properties of an NHPP such as thinning, and closure under superposition make it a robust model to analyze single as well as multi-hazard scenarios. However, when it comes to modelling the magnitude of these hazards using stochastic process models, the methods of probabilistic risk estimation for an NHPP assume them to be independent and identically distributed (IID) over time, which is not always the case, especially in this changing climate and this gap will be addressed here.

To estimate the losses due to these hazards governed by an NHPP with time-dependent rate functions and magnitudes, the definitions of NHPP are utilized to obtain a differential equation, the solution of which gives the expected values of the losses with time. Using similar arguments, the differential equations corresponding to other higher-order moments of the loss are obtained using a recursive formulation, which can be used to estimate the variance, skew, kurtosis etc. of the distribution of the losses. This method can be used to obtain discounted as well as undiscounted losses due to the hazards.

These results can find widespread application in risk estimation for any climate-driven hazard process and hence, provide economic grounds for justifying investment in climate change mitigation projects and adaptive measures. The optimal time for instigating the adaptive measures can also be predicted using these results. Not only that, this kind of economic analysis can used to predict the damage costs or cost of failures based on a given design and hence, prove to be a useful tool in risk-based design.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COARSE-GRAINED LATTICE DISCRETE PARTICLE MODELING OF ULTRA-HIGH-PERFORMANCE CONCRETE

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ABSTRACT

Ultra-high-performance concrete (UHPC) exhibits superior mechanical properties compared to traditional concrete thanks to its dense packing of aggregates and microfiber reinforcements. Accurate modeling of UHPC failure behavior relies on capturing the rich micromechanics of fiber-matrix interaction. In this regard, discrete models like the Lattice Discrete Particle Model (LDPM) with fiber(LDPM-F) have demonstrated excellent prediction of fracturing behavior UHPC with varied fiber content. LDPM-F models concrete at its coarse aggregate length scale and employs fiber-matrix interaction mechanisms to predict the accurate fracturing behavior of fiber-reinforced concrete without adding additional degrees of freedom for fiber elements. Nevertheless, simulating UHPC becomes challenging for structural length scale since commercially available UHPC contains aggregates with a maximum size of 600 µm. Lately, a mathematical coarse-graining (CG) approach was proposed for LDPM in which, a coarser representation of aggregates can predict the correct failure behavior of concrete by preserving the correct energy dissipation. In the current study, this approach is extended in the LDPM-F framework for simulating UHPC failure behavior with fiber. First, material-level tests, such as notched three-point bending, notched direct tension, and uniaxial compression, are simulated for different coarse-graining factors. Next, two dominant flexural failure modes with crack localization and strain-hardening in rebar-reinforced UHPC (R/UHPC) beams are simulated with coarse-grained LDPM-F model. Finally, a structural length scale R/UHPC beam is simulated for shear and flexural failure modes. Excellent predictions of fracturing and failure behavior are observed with coarse-grained models, proving the presented numerical framework's efficiency.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMAL TUNED MASS DAMPER CONTROL USING PARTICLE SWARM OPTIMIZATION ALGORITHM

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ABSTRACT

In the field of structural engineering, the tuned mass damper (TMD) stands as a pivotal element, strategically designed to mitigate vibrations in buildings and structures exposed to external forces, particularly seismic activity. This study delves into refining TMD design through the implementation of the Particle Swarm Optimization (PSO) algorithm for a ten-story building structure. The TMD optimization problem is formulated with two objective functions: Root Mean Square (RMS) of the top-floor displacement and acceleration. Parameters of the TMD, including the frequency ratio, mass ratio, and damping ratio, are systematically optimized within predefined bounds for the ten-story structure. Noteworthy is the distinctive approach of this study, which investigates the impact of various mass ratios on optimization outcomes. In the course of this investigation, time-domain analyses are conducted under diverse seismic conditions, encompassing both near-field and far-field earthquakes. These analyses yield valuable insights into the intricate relationship between TMD parameters and the characteristics of earthquakes, enriching our understanding of structural response optimization.

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-OBJECTIVE MULTI-AGENT DEEP REINFORCEMENT LEARNING FOR LIFE-CYCLE MANAGEMENT OF DETERIORATING SYSTEMS

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ABSTRACT

Deep Reinforcement Learning (DRL) has recently been proven to be able to provide advanced inspection and maintenance life-cycle policies for deteriorating infrastructure systems. Along these lines, our developed DRL architecture in [1], termed Deep Decentralized Multi-Agent Actor-Critic (DDMAC), utilizing the Multi-Agent Reinforcement Learning (MARL) paradigm of Centralized Training and Decentralized Execution based on Partially Observable Markov Decision Processes (POMDPs), is able to expertly address challenges associated with the curses of dimensionality and history, observation uncertainties, and presence of constraints. However, most current DRL implementations focus on single-objective optimization problem and cannot navigate trade-offs among multiple, conflicting objectives. The focus of this work is thus to extend the DRL-POMDP capabilities by developing novel techniques that can support multiple objectives and can thus provide relevant DRL solutions in the presence of the above-mentioned complexities. A straightforward approach to incorporate multiple objectives in the DRL framework is to use a scalarization function to essentially transform the multi-objective reward vector into a single scalar reward and then employ standard DRL algorithms to optimize this scalar reward signal. This approach of Multi-Objective Reinforcement Learning (MORL) falls under the category of single-policy methods, since each run results in a single optimal policy corresponding to a specific preference/parameter of the scalarization function. To learn an approximate coverage of the Pareto front, such MORL algorithms typically then combine single-policy runs with an outer loop that strategically choses scalarizations, with such approaches hence known as outer loop methods. In these methods, the agent lacks awareness of the scalarization parameters utilized, as these parameters are inherent to the environment, making it challenging to adapt easily to new preferences during implementation time. In order to overcome this limitation and extend MORL to multi-agent POMDP cases under constraints, preference-conditioned optimal policies are learned in this work, by augmenting the DRL input space with the preference weight space, leading to the development of an inner loop multi-policy approach that enables simultaneous learning of solutions on the Pareto front (or its convex approximation) for all preferences. The efficacy of the developed algorithm is illustrated on benchmark systems containing stochastically deteriorating components, and the performance is compared in detail with optimized multi-objective condition-based policy baselines.

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Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHALLENGES IN OFFSHORE PIPELINE INDUSTRY

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ABSTRACT

Subsea pipelines play a key role in the transport of hydrocarbon fluids. The traditional design practice in the pipeline industry led to over-conservative structures. With the paradigm shift, the pipeline industry is adopting the so-called ‘design through analysis’ approach where a finite element method is being employed in simulating the global behavior of pipelines. This presentation will focus on two problems specific to offshore structures. One of the major design checks focuses on the ‘on bottom stability’ of pipelines. A pipeline resting on a seabed is subject to external fluid loading from both waves and steady currents. Typically, this problem is formulated as simple force balance. However, this problem becomes more challenging in the case of shallow water, compared to deep water, due to the ergodic pattern of hydrodynamic forces. Additional complexity is invoked to the problem when the effect of pipe-soil interaction is considered. Therefore, detailed finite element analysis of ‘on bottom stability’ of pipelines remains an open area. The second challenging aspect is the engineering critical assessment (ECA) of girth weld in pipelines. Traditionally in the pipeline industry, engineers employ empirical relationships to perform fracture analysis, which is deterministic of nature. Development of probabilistic fracture mechanics-based methodology and tools in performing ECA of girth welds is another important area which needs improvement.

Advances in bridge health monitoring: Data-driven and machine learning methods, indirect monitoring, crowdsourced mobile sensing
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FINITE ELEMENT ANALYSIS OF STRUCTURAL BEHAVIOUR IN DAMAGED AND UNDAMAGED CONDITIONS: A CASE STUDY ON I-40 BRIDGE

Raj Singh[1], *Ishan Jha*[1], *Debarshi Sen*[2] *and Basuraj Bhowmik**[1]

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ABSTRACT

Finite Element (FE) analysis is a powerful technique for approximating solutions to boundary value problems, particularly in bridge engineering. This work presents a comprehensive study involving the modelling and analysis of a 3-span continuous I-40 bridge over the Rio Grande in Albuquerque, NM, using the ABAQUS/CAE software. The investigation aims to compare the behaviour of the bridge in undamaged and damaged conditions – focusing on modal properties, deflection, acceleration, and von Mises stress patterns. Comparing damaged and undamaged states in a structure aids in early detection and cost-effective maintenance [1]. The undamaged bridge model integrates concrete for the deck slab and steel for plate girders and stringers, following [2] and [3]. Dynamic properties, like frequencies and mode shapes, are obtained for the undamaged bridge. Various loads are applied to assess deflection, acceleration, and von Mises stress. The study explores cracks' effects on modal properties and structural responses. Results show increased deflection and von Mises stress with a crack in one-third of the plate girder's web bottom. Modal properties, frequencies, and mode shapes vary significantly between undamaged and damaged cases. Further exploration of crack location and size offers insights into their impact on structural behaviour. Key results reveal about 10.5% increase in maximum deflection at the mid-section upon introducing a crack in one-third of the plate girder's web bottom. Concurrently, von Mises stress values show an escalation under identical loading conditions. Resonant frequencies for the first, second, and third bending modes differ by 12.25%, 10.81%, and 11.14%, respectively, from experimental values. The resonant frequency for the first lateral mode is 6.41Hz. The study offers insights into I-40 bridge behaviour, informing maintenance and design.

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Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DECOUPLED BAYESIAN LEARNING OF PROCESS AND MEASUREMENT NOISE STATISTICS IN NONLINEAR KALMAN FILTERING

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ABSTRACT

Identification of states and parameters in nonlinear dynamical systems has been of great interest to the SHM community due to the importance of quantifying the effects of extreme loadings such as earthquakes. The Unscented Kalman filter (UKF) has been a popular choice among researchers for this purpose. However, the accuracy of the identified states and parameters is heavily influenced by the assumed process and measurement noise characteristics in Bayesian estimators like the UKF. Therefore, learning the noise characteristics becomes an essential aspect of Bayesian estimation, but is non-trivial in filtering and often raises non-identifiability concerns. In this study, we propose separating the measurement and processing noise learning algorithms in a fully Bayesian framework. For measurement noise estimation, we improve upon a Bayesian method that uses conjugacy of the inverse-Wishart distribution with respect to the Gaussian likelihood model. For process noise estimation, we use Bayesian model averaging to compare the performance of competing models with different process noise statistics. We also designed an improvement where low probability models are adequately altered to better explore the high-probability space of the unknown covariance. We tested our proposed approach on various numerical models, including linear and nonlinear systems and different noise identification cases.

LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS UNDER CLIMATE CHANGE

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ABSTRACT

Climate change due to global emissions of carbon dioxide will largely determine global warming trends over time with disruptive effects on the welfare of society. In particular, there is strong evidence that climate change will have significant impact on the temperature, precipitation and wind loads, which in turn will affect the safety, serviceability and long-term performance of structures and infrastructure facilities. However, traditional codes and standards as well as recently-implemented risk-informed performance-based design methods are founded on the assumption that historical climatic hazard data are stationary and do not currently consider the effects of climate change. To face this problem, the Structural Engineering Institute of the American Society of Civil Engineers, SEI/ASCE, has supported a special project as part of the activities of the Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems. This contribution describes the objectives of the special project, its organization, activities, and outcomes. Specifically, the project reviewed current knowledge about the effects of climate change on life-cycle performance, safety, reliability, and risk of structures and infrastructure systems, it appraised the applicability of existing data, outlined procedures to address the relevant issues and identified a set of research needs. The project also investigated various approaches for incorporating climate change effects in structural design codes and standards. The results of the project are expected to promote a better understanding of the problem and identify methodologies to account for the effects of climate change in the design of new structures and the assessment of existing structures.

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOWARD EXPERIMENTAL VALIDATION OF LIFE-CYCLE ASSESSMENT METHODS FOR CONCRETE STRUCTURES UNDER CORROSION

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ABSTRACT

Life-cycle-oriented design, assessment, maintenance, and management of deteriorating structures and infrastructural facilities, such as bridges, should rely on reliability and robustness analysis frameworks capable to account for time-variant structural performance under uncertainties. Although probabilistic life-cycle methods and deterioration models are well established for some of the most detrimental damage processes, such as corrosion, robust validation and accurate calibration are difficult tasks because of the limited availability of data about long-term performance of in-service structures. This study presents a computational framework and experimental validation procedures for life-cycle assessment of deteriorating structures under uncertainties, with a focus on life-cycle reliability and robustness of concrete bridges exposed to corrosion. The validation process is based on the results of experimental tests, including laboratory tests on corroded reinforced concrete beams available in literature and an extensive ongoing experimental campaign aimed at investigating the residual structural performance of a 50-year-old decommissioned prestressed concrete bridge (https://www.bridge50.org). Insights into some features of the damage process will be also provided, including the effects of spatial variability of corrosion and its impact on structural failure mechanisms.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SECOND-ORDER HOMOGENIZATION FOR MULTISCALE STRUCTURAL OPTIMIZATION APPLICATIONS

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ABSTRACT

Topology optimization and multiscale structural optimization have traditionally relied on numerical homogenization techniques to describe an evolving material domain. These homogenization techniques estimate the effective properties of a composite material through analysis of a microscale domain subjected to macroscopic conditions. This transition from the macroscale (observable) space to the microscale (material) space often requires restrictions on the size, form, and deformation modes of the microarchitecture. The most widely used form of homogenization in structural design defines these restrictions in terms of the (first-order) macroscale strains, assuming a strict separation of the macro- and microscales. Second-order homogenization, however, introduces the macroscale strain-gradient in the formulation of microscale boundary conditions to relax the required separation of scales in the first-order case. With this slightly relaxed model of scale separation, second-order techniques aim to model structures with observable hierarchy, i.e. structures composed of many spatially varying substructures at a manufacturable scale.

The second-order formulation introduces several challenges for design optimization that will be the topic of this presentation. The strain gradient introduces higher order stresses in the macroscale which require special treatment. In this work, we implement a mixed finite element scheme to enforce C1 continuity in the macroscale. In the microscale, where deformation is a function of the macroscale strain and strain gradient, more considerations are required for the application of periodic boundary conditions with ersatz materials. We present the numerical implementation of the second-order homogenization model in the context of structural optimization. Through comparison with first-order methods, the ability to model hierarchical structures is evaluated. We evaluate the behavior of second-order stress-strain relationships with the effective density of microstructural designs, producing the effective higher order properties of an evolving second-order material. Using this model, design optimization is performed using the second-order homogenization model with several canonical examples in structural optimization.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEW EXPERIMENTAL APPARATUS FOR TESTING OF THIN-WALLED SYSTEMS PRONE TO INSTABILITIES

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ABSTRACT

The complex behavior of structural instabilities is an area of continued interest. High-quality experimental techniques are necessary to accurately measure tested performance against analytical models. One area of current interest is steel decks which are formed from sheet steel into corrugated panels that are used to support roofs or floors in buildings. Testing bare steel deck assemblies loaded by jacks or actuators and spreader beams results in shear and moment envelopes that are not reflective of actual in-structure demand and may result in localized web crippling. To better represent uniform loading experienced by steel decks and steel deck and joist assemblies, a structural vacuum box, SEAhorse (Suction Experimental Apparatus), was designed and constructed. A sealed environment is created where industrial vacuums pull air out of the enclosed space, producing a negative internal pressure, which loads the test specimens with a uniform pressure across the deck surface. Valves are installed through the vacuum box wall to enable control of internal pressure drop. This presentation provides details on the vacuum box including its construction and operation. Next, the instrumentation that the vacuum box can support to obtain key test outputs is detailed. An infrared optical tracking system is used inside the box to measure displacements of the test specimens. Fiber optic cables are glued to the deck surface to measure distributed strain. Distributed strain represents the equivalent of multiple discrete stain gauges in a line, where the gauge length is dependent on the frequency of data recording and the total length of the cable.

A pilot experiment was conducted on a steel deck to test the capabilities of the vacuum box assembly and instrumentation layout. Fiber optic cables were glued in the longitudinal direction on several flanges of the deck, and transversely along the top flanges at a few locations on the deck. Conventional strain gauges were installed at select locations to compare against strains recorded by the fiber cables. Installing and calibrating the optical tracking system presented challenges due to limited distance between the cameras and the highly reflective deck surface. The deck was loaded to cause elastic local buckling in the bare steel deck compression flanges, which was captured by the instrumentation including distributed strain measurements. Details of the instrumentation setup to work inside the vacuum box in addition to challenges and benefits of the new test apparatus are presented.

Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING THE IMPACT OF CULVERT FAILURE IN THE FRANKLIN COUNTY WATERSHED

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ABSTRACT

Culverts are an integral part of the transportation infrastructure. They are susceptible to flooding-induced damage and failure, however often considered less important than bridges. Currently, culverts are not regulated. This means that communities often do not know where culverts or the condition of the culverts. Past research used a citizen science approach to create a detailed culvert inventory in the Franklin County Watershed located in northwest Massachusetts. This area is particularly vulnerable to flood events. Moreover, the rurality of northwestern Massachusetts means that a failed culvert may isolate large portions of the community. A culvert assessment procedure was created to be analogous to the bridge condition rating system maintained by the Federal Highway Administration. This system creates a risk of failure score composed of structural, hydraulic, and geomorphic risk factors associated with culvert failure. This component level score is not linked to an event; therefore, it cannot be treated as a typical fragility. Moreover, the component score does not provide a system level understanding of culvert failure such as inaccessibility to shelters or hospitals following a hazard event. This research addresses the pressing need to enhance the resilience of culverts by more accurately assessing the impact of their failure on the transportation system.

This study creates a geospatial network of the Franklin County Watershed to model the culverts and surrounding community. The risk of failure score is converted into a culvert failure probability while accounting for the uncertainty in hazard intensity and lack of available fragility for each of the culvers in the study area. Accessibility loss is measured using probabilistic connectivity metrics. The focus is on community accessibility to hospitals and shelters, which is most needed in the immediate aftermath of a hazardous event and when flood levels are at their highest. Finally, the study tries to incorporate social vulnerability by identifying the most relevant vulnerability factors within the area of interest. This study contributes to the growing discourse on infrastructure resilience, offering a more practical and multidisciplinary approach, which links engineering, social sciences, and risk assessment to foster more inclusive, sustainable, and disaster-resilient transportation networks.

THE IMPACT OF SURFACE ROUGHNESS ON THE SHIP’S RESISTANCE

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ABSTRACT

Recently, there has been an increasing focus on maritime transport, as it offers many advantages in terms of storage and transport. As a result, shipping companies need to reduce their vessels' fuel consumption. These companies have tried to define methods of operation and maintenance to reduce greenhouse gas emissions and also to reduce operating costs, thus increasing company profits. One important parameter that directly affects speed, power requirements, and fuel consumption is the hull resistance. Computational Fluid Dynamics (CFD) can be used to calculate the resistance of a rough surface using special wall functions that consider the effect of roughness on the boundary layer near the hull. These results can be compared with those of a smooth surface. In addition to the effect of surface roughness on hull resistance to pressure, this method also allows the combination of roughness and non-linear effects such as the spatial distribution of contaminants, the movement of the ship in waves, and the effect of thrust on hull resistance. Accordingly, this research aims to determine the effect of surface roughness on the ship resistance for different values of roughness height, boundary layer, and values of velocity, pressure, and kinetic energy fields for the KVLCC2 model hull by CFD using the RANS equations and the k-ω SST model. A numerical study was performed to determine how surface roughness affects the velocity field and kinetic energy.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND VULNERABILITY MODEL FOR COMPONENTS OF REFINERY PLANTS OR INDUSTRIAL FACILITIES: A PRELIMINARY STUDY

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ABSTRACT

The authors, with support from the Wind Hazard and Infrastructure Performance Center (WHIP-C), are developing wind vulnerability models of large industrial facilities like refinery plants. This research presents many challenges since these facilities are distributed over large plots of land which can have large variations in wind speeds, surface friction, topography, etc. At the same time, they can have a large variation in infrastructure components including power stations, pipe racks, tanks, warehouses, cranes, towers, etc. The authors propose to decompose the facilities into few sub-systems for which they can use conventional risk models: i.e., one site, one hazard, one vulnerability. Then they shall combine (not necessarily add) the models based on the inter-correlations between the sub-systems. In this so-called "Lego" approach, typical vulnerability components could be plugged in and interconnected, like Lego blocks, to produce an aggregated wind vulnerability of the whole system.

The authors shall report on the preliminary results of the research, which involve extensive literature review, consultations with experts and the prioritization of certain sub-systems for in-depth analysis. Key topics include understanding wind-related damage, determining the most vulnerable equipment, exploring sources of contaminant leaks, and reviewing existing specifications and mitigation plans, and developing component-based wind vulnerability models for tanks and pipe-racks. The research aims to enhance preparedness and to assess the risk in the face of wind hazards for industrial facilities. Special attention is given to the link between wind hazard and Natech accidents (i.e. technological disasters triggered by a natural event, in this case a wind storm). Catastrophic wind events can result in failures of industrial components which in turn can lead to release of toxic substances and failure of safety systems. Proper modeling of the wind vulnerability of industrial plants should lead to better management of the Natech risk. This topic should be of particular interest to the conference, given the incidence of climate change in the Americas, as exemplified by storm events in Brazil (Catarina in 2004), Mexico (Otis in 2023), and Argentina (December 2023).

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CT AND 3DXRD ON NON-IDEAL CRYSTALS FOR GEOMECHANICS APPLICATIONS

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ABSTRACT

This study aims to deepen our understanding of the strength and failure mechanisms in rocks by investigating grain-resolved stresses and their correlation with macroscopic stiffness and strength. We employ advanced techniques including X-ray tomography (XRT) for high-resolution 3D imaging and 3D X-ray diffraction (3DXRD) for tensorial grain stress measurements to fill the existing knowledge gap on grain-resolved stresses in rocks. We focus on discerning how grain stresses drive fundamental physical processes, including fracture, flow, dissolution, and precipitation. Key challenges in addressing this goal include: (1) applying XRT and digital volume correlation (DVC) to disordered microstructures with varying porosity characteristic of natural sandstones; (2) applying 3DXRD to non-ideal crystals which feature mosaicity and plasticity [1]. To address the first challenge, we apply open-source DVC codes to high porosity rocks to understand their grain kinematics and strain fields during triaxial compression. To address the second challenge, we develop a toolkit integrating ImageD11, HEXRD, and ML-based image segmentation software [2] to aid in processing diffraction patterns used for grain stress calculations. This research addresses current knowledge gaps in our understanding of the relation between microscale and macroscale mechanics in sandstones and offers avenues to study micro-macro relations in rocks and disordered and non-ideal crystals found in geology, materials science, and engineering applications.

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Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATION OF WIND FORCING ON THE ENERGY DISSIPATION OF SOLITARY WAVES IN A STORM SURGE

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ABSTRACT

Despite being a key aspect of the energy transfer between the ocean and atmosphere, the detailed dynamics of wave breaking, especially under the influence of wind, are not yet fully understood. We will conduct direct numerical simulations of two-dimensional solitary waves that shoal and break in shallow water on a uniform beach slope with an inundated inshore storm surge area, under low to medium wind loading conditions. The primary parameters are the beach slope, wave amplitude and wind speed. The wind energy input rate prior to breaking is determined and the wind effect on wave properties is tracked. The wave overturning is fully modeled, and both plunging and spilling breakers are observed. We will explore the wind loading effect on the breaker properties and the energy dissipation of the wave during breaking; and compare breaking energy dissipation rates with a current inertial model which was developed without consideration of wind.

AI-DRIVEN ASSESSMENT AND LARGE-SCALE MAPPING OF POST-DISASTER BUILDING DAMAGE BY INTEGRATING DEEP LEARNING, SATELLITE IMAGERY, AND GIS

Abdullah Braik[1] and Maria Koliou[1]*

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ABSTRACT

Efficient and accurate building damage assessment is crucial for effective emergency response and resource allocation following natural hazards. However, traditional methods are often time-consuming and labor-intensive. While recent advancements in remote sensing and artificial intelligence (AI), particularly deep learning, have made it possible to automate the damage assessment process, most prior research has focused solely on the technical aspects of machine learning classification. Addressing this gap, this study pioneers the practical application of AI as a disaster management tool by integrating deep learning, satellite imagery, and Geographic Information Systems (GIS). This integration enables the creation of comprehensive, large-scale building damage maps, providing valuable insights into the extent and spatial variation of damage. These maps serve as foundational tools for risk-informed decision-making and enable real-time updates of disaster management plans based on evolving on-site conditions. The effectiveness of this framework is demonstrated in Galveston County following Hurricane Ike, where it was used to automate the classification of tens of thousands of buildings and generate highly accurate large-scale damage maps that were validated against historical reports.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WOOD PILLARS STABILITY: EXPERIMENTAL RESULTS COMPARED TO BRAZILIAN STANDARDS

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ABSTRACT

This work presents the results of a laboratory research on the instability loads of wooden pillars compared to the values recommended by the Brazilian Standard for Design and Execution of Wooden Structures.
A Brazilian wood species called Jatobá was chosen, which can be classified as Class D60, that is, characteristic resistance to compression in the direction of the fibers 60 MPa. The slenderness of the specimens was varied from 20 to 110, in steps of 10, and 6 specimens of each slenderness were made, a total of 60 specimens.
Axial compression tests were carried out on the samples as bi-articulated, instrumented for lateral displacement at mid-span and for instability load. For each slenderness, mean and standard deviation of these loads were calculated.
Next, a comparison was made of the stress-slenderness curve obtained in the tests with the curves given by the Brazilian Standard for the Design of Wooden Structures, in its 1997 and 2022 versions, conceptually very different.
Good agreement was obtained between the 3 plotted curves.

Toward data-driven approaches for uncertainty quantification and propagation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CREATING A MULTI-FIDELITY SURROGATE FOR UNDEX EVENTS ON SHIP STRUCTURES

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ABSTRACT

Understanding how ships and other marine structures dynamically respond to shock events, such as an underwater explosion (UNDEX), is of critical importance, but gathering data for these events poses a daunting challenge. In the past the state-of-the-art for UNDEX events required destructive testing of real ships, an incredibly dangerous and costly practice. Within the marine structures community, there has been a recent pivot to digital twins as virtual representations of assets that can be used to track service life, maintenance, and repairs. The ability to perform UNDEX testing in the virtual environment on these digital surrogates would constitute a transformational improvement as compared to the current practice. However, this can only be accomplished with detailed modeling of the physics of failure for shock loads, which often leads to numerical simulations with incredibly expensive, if not prohibitive, computational costs. Multi-fidelity modeling methods have recently emerged as a means for relieving the computational burden associated with complex physics-based models without sacrificing accuracy. Multi-fidelity approaches utilize low-fidelity representations of a given system that can be run with minimal computational costs, albeit with reduced accuracy, and then intelligently combine those results with a few select results from a much more computationally expensive high-fidelity model.

This study presents a multi-fidelity modeling paradigm for UNDEX response prediction of a ship structure. The nature of ship structures permit low-fidelity representations in the form of free-free floating beams, modeled using classical Euler-Bernoulli beam theory. Conversely, advanced software packages such as MAESTRO provide high-fidelity models with detailed geometry. In both instances, the UNDEX event can be modeled as an oscillating, migrating pressure bubble that imposes a fluid acceleration on the ship structure. Using emergent techniques from the scientific machine learning community, a multi-fidelity surrogate is created by training on response data from both the low- and high-fidelity models. Details on the multi-fidelity approach and model architecture are discussed, and response prediction results are presented.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMAL KIRIGAMI-INSPIRED FAÇADE CUT DESIGNS FOR BUILDING ENERGY PERFORMANCE IN VARYING ENVIRONMENTAL CONDITIONS

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ABSTRACT

There has been growing interest in development of design concepts for building façade systems that can adapt to their environmental conditions naturally or through a control mechanism to improve some measure of performance [1]. For the example of photovoltaics integrated within a façade, adaptively controlling the orientation of the façade with respect to the sun can increase the effectiveness of the photovoltaics. Another concept is to adaptively open or close portions of the façade to control light or air entering the building. Many methods have been proposed to achieve adaptivity, with one promising approach being the use of intrinsic structural mechanisms, such as kirigami-inspired designs. In particular, kirigami-inspired façade components could potentially benefit solar tracking, ventilation, and other building performance metrics [2]. Although promising, relatively few design options have been considered, limited design objectives have been quantified, and minimal work has been done to evaluate the potential impact on building performance. The present research is establishing numerical approaches to evaluate the potential effect of kirigami-inspired façades and optimize their design for building energy performance. More specifically, this presentation will consider a kirigami-inspired façade design with variations in size, spacing and curvature of the cuts, towards the objective of optimal building performance. Building performance will be quantified with respect to energy cost and energy gained from irradiance and ventilation functions. The computational approach to evaluate building performance utilizes finite element analysis to predict the mechanical response of the façade component, which is then combined with analytical environmental models to estimate irradiance and ventilation with respect to given environmental conditions. The performance estimate is combined with an iterative optimization algorithm to estimate the parameters of the cuts design for a component to maximize energy and ventilation performance of the building subject to constraints on material limits, structural stiffness, and internal temperature. Several building scenarios will be considered as test cases and the most effective cut design for each test case will be defined.

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Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ESTIMATION OF THE MECHANICAL PROPERTIES OF IN VIVO CERVICAL SPINE INTERVERTEBRAL DISCS

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ABSTRACT

Progressive deterioration of the intervertebral discs of the cervical spine is a potentially serious health condition that is often related to aging and a variety of mechanical factors. Spinal fusion is the most common surgical procedure to treat symptomatic disc degeneration. However, post-surgery, patients may experience degeneration of another disc, which is assumed to be linked to the altered mechanical stresses within the cervical spine due to the fusion. Yet, the specific mechanisms behind this phenomenon remain unclear. To better understand how mechanical stresses change after fusion surgery and their impact on individual intervertebral discs, an important first step is to establish an approach for meaningful subject-specific mechanical analysis of cervical spine mechanics. Towards this goal, the current objective is to create an approach to estimate the subject-specific material properties of intervertebral discs from in vivo imaging data during motion. First, a subject-specific cervical spine finite element analysis process was established. In this study, CT scans of the cervical spine with an average resolution of 0.30×0.30×1.0 mm are utilized, and 3D geometries of the vertebral bodies are extracted for the cervical spine (vertebrae C2 to C7). Then, intervertebral disc geometries, including annulus with embedded fibers and nucleus, are approximated based on the spacing between the vertebrae. The size is estimated so that the nucleus is between 40% to 50% of the total volume of the disc. Facet cartilage is also included to simulate the articulation between the posterior elements of adjacent vertebrae. Each tissue component is assumed to be homogeneous with elastic and isotropic material properties, and initial material parameters are assigned to each component based on published values. Boundary conditions are set such that the inferior endplate of C7 is fully constrained. Intervertebral motion data from multiple motion trials of a given subject, acquired with submillimeter accuracy using biplane radiography, are then used to calibrate the disc material properties and ultimately validate the calibrated spine mechanical model. In addition to presenting this analysis procedure, examples will be considered in which this approach was applied to estimate disc properties for several in vivo human trials. Longer-term objectives include further improving the patient-specific mechanical modeling approach, for example, by including ligaments and evaluating their effect on the mechanical response of the intervertebral discs. The ability to non-invasively estimate disc mechanical properties using computational models may one day help guide clinical treatments to delay or reverse disc degeneration.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MONITORING TO LOCALIZE EXCESSIVE VIBRATIONS IN HYDRAULIC STRUCTURES

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ABSTRACT

Excessive vibration in hydraulic systems can lead to fatigue issues and eventual failure of a system. Determining the source and cause of the vibration is essential to evaluating the structural integrity and ensuring its continued operation. In hydraulics systems these vibrations are often caused by leakage flow as water rushes through gaps between parts. At a hydropower plant in Arkansas, a short-term monitoring program was designed using accelerometers to localize the source of vibration coming from an offline hydropower unit. While online, the hydraulic head upstream of the hydropower station and the opening and closing of wicket gates within the unit controls the amount of water that passes through to spin the turbine. In the offline state, the wicket gates are fully closed, and no water should be allowed to pass through. Observations made by onsite personnel led to the belief that leakage-flow induced vibrations were occurring due to gaps between adjacent gates outside of the allowable tolerance. The results of this effort led to determining the source of vibration by calculating the energy of vibration for each wicket gate as the gates transitioned from opened to closed. At sector gates in a lock chamber in New Orleans, cracking occurs on the horizontal girders at the top and bottom of the ears of the gates. This cracking eventually led to major repairs and a partial redesign of the gates. When operating the chamber, the water level is controlled by opening the gates partway to allow water to pass by the ears and fill or empty the chamber. It is believed that the cracking forming in the ear could possibly be fatigue cracking from flow-induced vibrations as the water vibrates the ears as it flows past, causing a high number of fatigue cycles. A finite element model was created to identify whether the cracking formed could be explained by excessive vibrations and to aid in the design of a monitoring program to examine this issue.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PREDICTION OF MECHANOSORPTIVE CREEP IN MASS TIMBER VIA MICROPRESTRESS THEORY

Susan Alexis Brown[1], Giovanni Di Luzio[2] and Gianluca Cusatis[3]*

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ABSTRACT

Recent focus on sustainability in structural design has led to the implementation of a variety of novel building materials, as well as the resurgence of old material such as timber. However, despite the historical legacy of wood in structures, there are many factors which have not been fully investigated for large scale applications, i.e. wood buildings above five stories. On such aspect is the long-term deformations in timber structural components, and specifically the influence of moisture and temperature rate changes on such deformations. This work thus shows how the application of the microprestress theory for partially saturated porous materials is applicable to mass timber applications and can be used to predict creep deformations at the structural component scale. Results indicate general agreement with existing data and are applicable to multiple species and loading conditions. Long-term predictions also indicate areas of concern in current building code prescriptions for long-term deformations in mass timber.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATION HISTORIC MASONRY STRUCTURES USING NONDESTRUCTIVE, DESTRUCTIVE, AND ANALYTICAL TOOLS

Peter Babaian[1] and Connor Bruns[1]*

[1]Simpson Gumpertz & Heger

ABSTRACT

Historic masonry structures are constructed with varying materials and methods. Brick, stone, and mortar can be based on local availability while masonry thickness and bond patterns may depend on empirical construction practices. While these structures can be long-lasting, the materials and details of construction are critical to the evaluation of their behavior, especially when stress analysis is required to validate the cause of deterioration. Non-destructive and destructive methods can be employed to determine the masonry composition, properties, and details. Combined with analytical tools, this information can be used to evaluate load path, validate stress concentrations, and confirm cracking patterns. This presentation will show how application of these methods can be used to analyze a 120-year old academic building with a deterioration pattern that did not match typical expected deterioration for a load bearing masonry building. Non-destructive, destructive, and computational analysis techniques developed understanding of the behavior and issues, which in turn allowed for solutions to address them.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE EFFECTS OF AGE, SEX, AND THE MATERIALS OF HIP IMPLANTS ON THE MICROSTRUCTURES AND MECHANICAL PROPERTIES OF HIP CAPSULE SCAR TISSUES

Angelina Avgeri[1], Samantha Sanders[2], Bertrand Cinquin[3], Christophe Sandt[4], Laurent Sedel[5], Pascal Bizot[1] and Elisa Budyn[2]*

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[3]Institut Pierre Gilles de Gennes
[4]SOLEIL Synchrotron
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ABSTRACT

The hip capsule is a fibrous connective tissue that plays a stabilizing role in the hip joint and on the motion of the joint. Following a total hip arthroplasty, the hip capsule is often either damaged or removed. During the recovery of the surgery, a fibrous scar tissue forms that exhibits different morphological and mechanical differences from the native tissue. These new properties are linked to the interactions of the material with the materials of the hip implants, but also age and sex that are known to influence the ligament structural and mechanical properties. Variations in collagen and elastin contents and different fiber organizations have been observed in the scar tissues. In this study, the hip capsule tissues that has formed around different implant materials have been compared to the native hip capsule tissue. The morphological properties of these tissues have been investigated by multiple histological staining for Type I, II and III collagen and elastin. The mechanical properties of the tissues have been investigated by tensile micro tests. The load-deflection responses of the tissues have been compared with respect to the implant materials, the testing load-cells, the patient ages or sexes. Differences between male and female patients showed that female tissues tend to be more flexible than male tissues. Overall, all the scar tissues are also shown to be stiffer than the native tissue.

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Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MOLECULAR DYNAMICS AND QUASICONTINUUM STUDIES TO EXPLORE PARALLEL STRESS EFFECTS ON FRACTURE MECHANISMS AT THE NANOSCALE

Yu-Chuan Hsu[1], Steve M. Whalen[2], Woo Kyun Kim[3], Zdeněk Bažant[4], Ellad B. Tadmor[2] and Markus Buehler[1]*

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ABSTRACT

The parallel stress effect is a phenomenon whereby a material, when exposed to different levels of compressive stress in the direction of the crack, exhibits variations in the ultimate strength and fracture energy. This behavior has been theoretically predicted and experimentally verified and shown to have a significant impact on the fracture behaviors of materials such as concrete, fiber-polymer composites and aluminum alloy, with real-world impacts on reliability and service life. In this study we use atomistic-level modeling to describe this phenomenon in a series of model materials including graphite. We examine tensile test simulation cases under different levels of in-plane compressive loads to explore associated fracture mechanisms and changes in ultimate strength and fracture energy. We compare our findings with theoretical predictions and experimental results.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AGENTIC LANGUAGE-BASED STRATEGIES FOR MECHANICS AND MATERIALS MODELING TO CONNECT SCALES, DISCIPLINES, AND MODALITIES USING HIERARCHICAL ARCHITECTURES

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ABSTRACT

For centuries, researchers have sought out ways to connect disparate areas of knowledge. While early scholars (Galileo, da Vinci, Goethe, etc.) were experts across fields, specialization took hold later. With the advent of Artificial Intelligence, we can now explore relationships across areas (e.g., mechanics to biology) or disparate domains (e.g., failure mechanics to art). To achieve this, we report the development of a series of multimodal large language models (LLM) based on attention-based modeling, arranged in a complex multi-agent framework. The modeling strategy includes the use of a general-purpose LLM to distill question-answer pairs from raw data like text, simulations and other sources followed by fine-tuning, and the deployment of multimodal agentic frameworks to solve a series of complex forward and inverse problems. Case studies presented include multiscale models of failure, hierarchical composite design, and de novo protein development. Specific focus of all studies is on mechanics-focused properties, especially deformation and failure and the incorporation of physical constraints, closedness, and data generation via active learning. In addition to agentic modeling, we also discussed the incorporation of mixture-of-expert models to enhance capabilities of models across modalities, expertise and scales as another hierarchical scheme to construct powerful models.

Small scale phenomena in sustainable & complex materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELUCIDATING THE ENHANCEMENT MECHANISMS OF CARBON NANOMATERIALS IN FINE RECYCLED CONCRETE AGGREGATE MORTARS

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[2]North Carolina State University

ABSTRACT

The application of recycled concrete aggregates in new concrete has the potential to decrease the embodied energy and carbon dioxide of concrete while also alleviating landfill space shortages and contributing to the growing yearly demand for aggregates. However, recycled concrete aggregates negatively impact the mechanical properties and durability of concrete due to the inhomogeneous, porous, and cracked nature of the residual binder. Carbon nanomaterials, such as carbon nanofibers (CNFs) and multi-walled carbon nanotubes (MWCNTs), have emerged as promising additives to overcome the reduced mechanical properties and durability that are caused by recycled concrete aggregates. Yet, the very few studies that have investigated carbon nanomaterials in recycled aggregate concrete have focused on macroscopic properties and a multi-scale understanding of the enhancement mechanisms is lacking. In this research, we aim to connect the structure of the calcium-silicate-hydrates (C-S-H) gel to the fracture toughness, chemical composition, microstructure, and pore structure of fine recycled concrete aggregate (FRCA) mortars with CNFs and MWCNTs. For this goal, we synthesized nanomodified FRCA mortars using a novel processing method and employed nanomechanical testing, data science, and advanced analytical characterization techniques. From our analysis, we find that CNFs increase the combined relative amount of high-density and ultra-high-density C-S-H by 62.7% in addition to decreasing the porosity by 8.9% and increasing the fracture toughness by 6.7%. On the other hand, we find that MWCNTs increase the combined relative amount of high-density and ultra-high-density C-S-H by 35.7%, decrease the porosity by 10.0%, but do not increase the fracture toughness. The results of our study provide fundamental insights into how nanomaterials can be used to develop high performance and sustainable construction materials that utilize recycled concrete aggregates.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN INVESTIGATION INTO THE ROBUSTNESS OF INSPECTION AND MAINTENANCE STRATEGIES TO MODEL ERRORS

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ABSTRACT

Since society is dependent on its infrastructure systems, it is essential that they operate reliably, safely, and cost-effectively. Infrastructure operators apply inspection and maintenance (I&M) strategies over the structure's lifetime to prevent failures, but these are typically based on simple rules and regulations and might be suboptimal. One difficulty in optimizing inspection and maintenance strategies is the lack of accurate deterioration models. The challenge of designing an exact model for the deterioration of a system is due to large uncertainties in environmental factors, materials, inspection quality and other known or unknown influencing factors. Usually, multiple trajectories of the model are projected to train I&M strategies in simulation, significantly reducing the amount of time and data required. However, small model errors can result in big differences when executed in reality. This is known as sim-to-real gap, with some solutions being domain randomization, domain adaptation, and imitation learning. Domain randomization has been applied to I&M problems to obtain robust strategies in [1, 2].

In our work, a robust strategy is defined as one that performs well if the simulation model used to determine the optimal I&M strategy differs from reality. Here, two questions need to be clarified: How do we measure performance? How do we measure the discrepancies between model and reality? For this, we implement a simple example of a stochastic deterioration model and identify near-optimal I&M strategies via heuristics. Secondly, we propose a measure for quantifying the sim-to-real gap. Furthermore, we investigate different heuristics forms, including some corresponding to condition-based and some predictive maintenance strategies. We then systematically vary the sim-to-real gap and test numerically how the performance of the trained strategies changes with increasing sim-to-real gap. Following, we draw conclusions on which strategies are more robust and which types of sim-to-real gaps are more critical for the performance of trained strategies in the real world.

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New challenges in instabilities of shell structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL CHARACTERIZATION OF THE MECHANICAL BEHAVIOR OF A STEEL LINER SUBJECTED TO HIGH CONFINEMENT BASED ON IN-SITU MEASUREMENTS

Frederic Bumbieler[1], Norman Mathieu[2], Mohamad Jrad[2] and Gilles Armand[1]*

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ABSTRACT

Ensuring structural reliability of tubular confined structures subjected to external loading is a major challenge in numerous applications: well casing in oil and gas industry, buried pipelines, pipe in pipe systems for damaged pipelines rehabilitation and deep geological repository for radioactive wastes. Within this context, the mechanical behavior of an API5L steel liner of deep micro-tunnels excavated in the Callovo Oxfordian claystone is investigated by Andra in Meuse-Haute Marne Underground Research Laboratory. The numerous full-scale in-situ experiments carried out since 2010 highlight perfectly reproducible mechanical response of the liner to anisotropic loading applied by the confining medium. The resulting ovalization rate decreases with time to reach 10-11 s-1 after a few years. The influence of a cement grout backfilling of the annular space between the liner and the rock is discussed with respect to ovalization process. Two heating experiments were also implemented to analyze the influence of a thermal load. After a few months transient phase of ovalization acceleration, mainly due to thermal expansion of the surrounding rock, convergence rates return to those prior to heating.

Based on liner convergence and circumferential strain measurements, an inverse method has been developed to estimate the radial loading applied on the liner and its time evolution. Simplified loading cases decoupling spatial and time evolutions and considering a sinusoidal distribution of the radial load around the liner, have been obtained by minimizing a cost function describing the difference between experimental measurements and numerical simulations. The main loading parameters governing the mechanical response of the liner are analyzed and discussed.

Repair and assessment of deteriorating critical infrastructure
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSMENT OF MASS CONCRETE STRUCTURE JOINT CONDITION BY APPLICATION OF IMPACT LOADS FROM A COLD GAS THRUSTER

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ABSTRACT

Modeling and monitoring mass concrete structures can be difficult due to the relative dearth of failure examples and difficulty determining the boundary conditions at the foundation and between monoliths. The condition of joints is of particular interest, especially as the joints are considered a likely point of failure in dams. Acquiring information on their state is also important both for general structural health monitoring and for assembling accurate models. The Cold Gas Thruster (CGT) is a method of inducing a pulse load to a structure. It has previously been established to induce global modes of vibration with potential of detecting changes in boundary conditions (Riveros, 2023). The modal response of a structure is changed when the interactions between masses in the structure are changed. In this work, a test lock wall with an aged neoprene vertical joint and several horizontal cold joints was tested using the CGT and accelerometers placed on either side of the various joints as well as at the center of the lifts and near the top of the structure. The CGT was placed at the top of one of the two monoliths and fired so that the load went in the direction orthogonal to the plane of the wall. Comparisons of the Shock Response Spectrum (SRS) of accelerometers placed on either side of joints and Cross Power Spectral Density (CPSD) of the time histories reveal what are typical changes to vibrational content across joints of different types. The vibrational content of different monoliths is dependent both on distance from the CGT and what joints are between the accelerometer and the CGT inducing the impulse. Changes to a joint condition will likewise change what vibrations are attenuated or pass through a joint, with a more significant deterioration lowering the frequency that is attenuated across the joint. This work may allow joint condition to be determined with nonpenetrative physical testing, as the CGT is lighter and easier to apply than shakers for a modal analysis and dams often lack the traffic to induce sufficient modal action.

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Complex dynamics and vibration control of infrastructure exposed to single/multiple hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMIC RESPONSE OF HYBRID MASS TIMBER-STEEL BUILDINGS USING REAL-TIME HYBRID SIMULATION

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[1]The Pennsylvania State University

ABSTRACT

Under earthquake events, the complexity of the dynamic response of hybrid mass timber-steel structures is strongly influenced by the combination of different mechanical properties and the configuration of the force-resisting systems. For instance, the interaction between cross-laminated timber (CLT) floor diaphragms and steel lateral moment-resisting or braced frames can describe the complex dynamics along with its limitations in the system-level performance under different earthquake hazard levels. To explore the dynamic response and the implications on the linear/nonlinear seismic performance of hybrid structures, real-time hybrid simulation (RTHS) is a powerful framework that enables the integration of numerical and experimental substructures to capture and comprehend better the full extent of the structural response and replicate realistic dynamic loading conditions to this type of structures. This research investigates the global dynamic response and the seismic performance of a rectangular 4-story hybrid CLT-steel building using RTHS. The contribution of the in-plane stiffness from the CLT floor diaphragm to the dynamic response and the implications on the seismic performance of the steel lateral force-resisting frames are evaluated to understand the system-level performance. The experimental substructure consists of a small-scale configuration of CLT panels and steel frame members, while the numerical substructure represents the remaining finite element model of the building. This proposal facilitates the study of rate-dependent components of hybrid mass timber-steel structures and the comparison between numerical modeling and hybrid simulation results by implementing a cost-effective method without replicating full-scale tests.

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INFLUENCE OF AXIAL LOAD ON THE LATERAL BEHAVIOR OF BUILDINGS WITH A WEAK GROUND-STORY

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ABSTRACT

During intense earthquakes, a considerable number of medium-rise buildings with an open ground story (OGS) exhibits severe structural damage that results in collapse. The collapse of these buildings is mainly due to failure of their ground story, which has led to the concept of weak ground-story (WGS). In many cases, these buildings change their use with respect to that considered during their design, resulting, generally, in an increase in vertical loading. Considering that the nonlinear response of a WGS is strongly influenced by the lateral behavior of the ground story, it is necessary to determine the effect of axial loading on its nonlinear response, particularly on a possible and significant reduction of its ultimate lateral deformation capacity. Therefore, this paper studies the lateral behavior of medium-rise buildings with a WGS, designed according to the Mexico City Building Code (MCBC-2020). The structural system of the buildings is composed by a ground story conformed by a reinforced concrete (R/C) moment-resisting frame, and a superstructure conformed by confined masonry walls. A nonlinear modelling approach, extensively calibrated with experimental data, is used to develop analytical models of the buildings with the OpenSees software. A series of nonlinear pushover analyses (NPA) and nonlinear dynamic time-history analyses (NDTHA) are performed to study the influence of an increasing axial loading in the columns of the ground story in the seismic performance of the buildings. From the resulting capacity curves and the inter-story drift index (IDI) distribution along height, it is concluded that axial loads have a significant effect on the behavior of the ground story, suggesting that seismic design codes should limit the level of axial load acting on the ground story columns when a change of use is required in this type of buildings.

EXPLORING THE IMPACT OF SEISMIC DEMAND MODELLING ON THE OPTIMUM SEISMIC MONITORING LAYOUTS

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ABSTRACT

Over the decades, numerous Ground Motion Models (GMMs), which are the tools to estimate the level of ground shaking in terms of Intensity Measures (IMs) such as Spectral Acceleration (SA), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), along with their inherent uncertainties have been developed. These models are formulated as a function of the ground motion characteristics such as the magnitude of an earthquake, site-to-source distance, style of faulting, and other seismological parameters. The ever-growing high-quality strong ground motion databases provided by several authorities foster the ongoing advancement of these models, given that their formulation relies on the regression analysis conducted on the selected databases. Furthermore, the increased number of recorded ground motions allows for the renewal of the Earthquake Rate Models (ERMs). These GMMs and ERMs are the pivotal components of the Probabilistic Seismic Hazard Assessment (PSHA) and therefore many of the earthquake- and structural-engineering applications such as the Seismic Emergency Management. As mentioned in [1], the ongoing development of components in PSHA leads to various equally valid hazard maps. Furthermore, the increasing number of GMPEs introduces challenges in selecting the appropriate models for the region under consideration. In this study, the assessment is made for the optimal layout of ground motion sensors to be deployed across a network of bridges, serving seismic emergency management purposes. The central Italy is selected as the study region and different ERMs applicable to the region are utilized to generate possible scenario earthquakes. The seismic demand at the location of the bridges that forms the transportation network under consideration are evaluated using different GMMs, which are selected using the procedure provided in [2]. This study, principally investigates the effects of the assumptions made in the seismic demand modelling utilizing different GMMs and ERMs on the selection of the optimum sesmic monitoring layout utilizing the Value of Information (VoI) theory.

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Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

3D FINITE ELEMENT ANALYSES OF MULTISTAGE FIBER REINFORCED BEARINGS (MS-FRBS) IN DIFFERENT CONFIGURATIONS

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ABSTRACT

Base isolation (BI) is a well-consolidated passive seismic protection technology, and rubber-based devices such as Laminated Rubber Bearings (LRBs) have been widely adopted on a global scale. A low-cost alternative, Fiber Reinforced Bearings (FRBs), has been gaining momentum in the last decade. However, applying this technology to lightweight structures or non-engineered buildings (N-EBs) poses challenges due to the need for slender bearings with potential stability issues. The Multistage Fiber Reinforced Bearings (MS-FRBs) were recently proposed as an innovative BI system that uses unbonded rubber bearings in series to achieve a stable and tunable response in both the vertical and horizontal directions. This paper presents the results of a comprehensive numerical investigation through 3D finite element analyses (FEAs) on MS-FRBs with square shapes. The study demonstrates how this technology may improve the responses of a BI system under different loading conditions. The results underline the potential of MS-FRBs across various applications, presenting specific advantages that position them as a promising solution for BI of both structures and artifacts. This includes the protection of lightweight artifacts, a challenge traditionally associated with rubber-based devices due to instability concerns arising from the use of slender bearings.

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRAGILITY ASSESSMENT OF INDUSTRIAL COOLING TOWERS UNDER HURRICANE WIND LOADS

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ABSTRACT

Industrial complexes such as refineries and petrochemical facilities are comprised of multiple process units and auxiliary components such as Cooling Towers (CT). In the US most of these facilities are in coastal regions prone to tropical cyclones that are being exacerbated by climate change in frequency and severity. In the Gulf Coast, previous hurricanes caused severe damage to industrial buildings that lead to operational disruptions and economic losses. Reports suggest that CT experienced substantial damage to cladding and components (C&C) as well as partial or complete collapse due to extreme wind loads. While the direct repair or replacement cost for these structures may be low relative to other process units or to daily revenue, their failures can jeopardize the entire operation and result in significant business interruption (BI). Besides affecting companies' productivity, BI negatively impacts the economy and energy accessibility of coastal communities that are highly vulnerable after a hurricane event. Despite the historic evidence of vulnerability and acknowledgement of their criticality to coastal industrial operations, comprehensive fragility analysis of CT under extreme weather events is lacking.

This work presents a rigorous and comprehensive methodology for calculating parametrized fragility models for typical CT buildings typologies (i.e. counterflow and crossflow) extensively found in the US Gulf Coast industrial corridors under hurricane wind loads. The proposed fragility functions consider probabilities both for C&C failure and for structural collapse of CT. For the latter, bracing buckling and support loss failure mechanisms were considered and assessed using finite element analysis. For C&C, support and anchorage failure fragilities were derived using analytical limit state functions that consider fatigue.

Stochastic hurricane wind models and machine learning techniques trained with wind-tunnel data were leveraged for the hazard and load model, respectively. A probabilistic assessment of the joint probabilities of hurricane wind velocity and direction was conducted. Convolving the hurricane hazard and the parametrized fragilities, a probabilistic risk assessment was performed as a case study for numerous CT located in the Houston Ship Channel industrial corridor. The results present the first comprehensive assessment of the failure probabilities of CT and allow estimation of functionality impact to industrial complexes, providing a basis for risk mitigation and resilience quantification in the future. The insights suggest that decision makers should focus their attention to improve the resilience of the physical industrial infrastructure to minimize BI that led to economic losses but also affect the energy access and economy of coastal communities.

Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING ELECTRICAL DISTRIBUTION NETWORK RESILIENCE TO WILDFIRES THROUGH SIMULATION AND RISK ASSESSMENT.

Richard Campos[1], P. Scott Harvey[1] and Kanthasamy K. Muraleetharan[1]*

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ABSTRACT

This study explores the impact of wildfires to electrical distribution networks, specifically focusing on the Southern Great Plains. Over the past decade, wildfires have burned millions of acres, causing significant damage to infrastructure, resulting in substantial repair/replacement costs. The surge in wildfire frequency is attributed to climate shifts, evolving land cover, and socioecological conditions. Additionally, a recent wildfire outbreak in Oklahoma has raised concerns, leading to a proactive effort by Oklahoma NSF EPSCoR researchers to enhance the resilience of the state's infrastructure and communities to wildfires. This study utilizes a developed probabilistic framework to assess the resilience of a power distribution network in Oklahoma. Component fragility analysis is used to evaluate the vulnerabilities of the electrical distribution components (e.g., power poles and lines), to address potential weak points in the network. The analysis considers important wildfire factors such as fire weather and topographical conditions. Wildfire simulations in FARSITE are used to provide a dynamic understanding of the wildfire risk in the region, where region-specific parameters are determined through Monte Carlo parameter estimation. This study offers valuable insights into enhancing the resilience of electrical distribution networks. The emphasis on resilience frameworks and component fragility analysis contributes to a nuanced understanding of the evolving wildfire problem in the Southern Great Plains, aiding in the development of targeted strategies for electrical network enhancement and emergency management.

On the mechanics of road and paving materials in the cold, Nordic, and Arctic Regions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING PREDICTION OF THE MECHANICAL RESPONSE FROM CHEMICAL CHARACTERISTICS OF ASPHALT BINDERS USED IN THE NORDICS

Fan Zhang[1]*, Augusto Cannone Falchetto**[1] *and Di Wang*[1]

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ABSTRACT

The change that occurred in recent years to the asphalt binders market has strongly impacted the pavement industry in the Nordic countries in Europe, demanding alternative and practical approaches to the evaluation of their mechanical properties. It is known that there is a strong correlation between the rheological and chemical properties of asphalt binders [1]. If advanced machine learning tools can be introduced to predict the rheological behavior of binders based on their chemical properties, then it can dramatically reduce the experimental time and increase working efficiency, as well as provide rapid characterization for asphalt samples. With this objective, binders with different grades, sources, and batches are collected. Fourier transform infrared spectroscopy (FTIR) and dynamic shear rheometer (DSR) are adopted to measure the chemical and rheological properties of binders. Different machine learning methods, including principal component analysis (PCA), multiple linear regression (MLR), and Gaussian process regression (GPR), are introduced to achieve the prediction purpose. Results indicate that binders have six similar typical bond areas, but different grades, sources, and batches can affect the area value. DSR test reveals that the rheological properties of binders are significantly affected by temperature, and viscoelastic transition occurs at the mid-temperature region. The raw six FTIR features can be reduced to two principal components (PC 1 and PC 2) based on PCA. The variance and role of PC 1 are more significant than PC 2, and the raw features are all positively correlated with PC 1. MLR model can predict the phase angle accurately but not for modulus. A GPR model with higher R2 and lower Root Mean Squared Error (RMSE) values can accurately predict both modulus and phase angle. The frequency-independent variable alone shows no correlation in these two models, but the temperature-independent variable is highly correlated. Comparing these two models, the evaluation indicators (R2 and RMSE) perform more accurately for the GPR model, but this requires higher configuration and longer computing time. This work can significantly improve the experimental efficiency and has great meaning for the rapid characterization of binders, leading to considerable production benefits in the cold Nordic climate, where prompt and precise decisions in the selection of the binders are essential.

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On the mechanics of road and paving materials in the cold, Nordic, and Arctic Regions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTIPLE RECYCLING OF ASPHALT PAVEMENT IN COLD CLIMATES

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ABSTRACT

The growing emphasis on increased sustainability within the pavement industry has led to a substantial surge in the utilization of Reclaimed Asphalt Pavement (RAP). As the next generation of pavements is anticipated to undergo multiple recycling cycles, a critical question arises regarding the potential impact on the durability and long-term performance of road infrastructure. Addressing this inquiry, our study undertakes an experimental investigation into the effects of multiple recycling (extending up to three generations) of RAP on performance properties and susceptibility to moisture damage. Leveraging prior research efforts in Finland [1] and employing laboratory experimentation, loose asphalt mixtures underwent controlled aging in an oven to produce RAP subjected to one, two, and three aging cycles. Subsequently, a series of asphalt mixtures were formulated, incorporating 50% of artificially aged RAP, creating distinct sets representative of different recycling levels. Comprehensive testing, encompassing assessments of moisture susceptibility, resistance to rutting at elevated temperatures, and abrasion resulting from studded tires, was conducted on the entire spectrum of asphalt mixtures. Remarkably, as the recycling iteration increased, recycled, re-recycled, and tri-recycled asphalt mixtures exhibited enhanced properties in terms of moisture susceptibility, rutting resistance, and resistance to abrasion from studded tires when compared to their conventional asphalt counterparts.

This experimental endeavor not only substantiates the feasibility of exploring multiple recycling of RAP in the Nordic regions but also contributes valuable insights into the potential improvements in performance properties associated with successive recycling cycles. The findings underscore the viability of incorporating sustainable practices in pavement engineering, with implications for future research endeavors and policy considerations within the domain of road infrastructure development in cold climates.

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Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL TIME HYBRID SIMULATION (RTHS) OF A 2-STORY REINFORCED CONCRETE BUILDING EQUIPPED WITH A NOVEL SELF-CENTERING BASE ISOLATION SYSTEM

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ABSTRACT

A new semi-active friction device using band brake technology, termed the Banded Rotary Friction Damper (BRFD), has been fabricated at the NHERI Lehigh experimental facility. The damping mechanism is based on band brake technology which leverages a self-energizing mechanism to produce large damping forces using a low-energy input. The BRFD generates a damping force as a function of the input force provided by two electric actuators, where the ratio of BRFD force output-to-electric actuator force input exceeds a value of 100.

The presentation will present the results of a study using real-time hybrid simulation (RTHS) to investigate the performance of the BRFD's in mitigating seismic hazards on a two-story reinforced concrete building. The building has two and three special moment resisting frames (SMRFs) in the east-west and north-south directions, respectively. In order to perform a RTHS, the north-south SMRF is considered and a Self-Centering Banded Rotary Friction Device (SC-BRFD) is positioned as a base isolation system to mitigate the effects of earthquake hazards. For the RTHS, the building and the nonlinear self-centering component of the SC-BRFD isolator are part of the analytical substructure while the BRFD forms the experimental substructure. The response of the structure is investigated involving six design basis earthquake (DBE) level events that include three near-field and three far-field earthquakes. The explicit, unconditionally stable dissipative Modified KR-α integration algorithm is used to accurately integrate the equations of motion during the RTHS. The model for the reinforced concrete building is created using explicit non-linear force-based fiber elements to discretely model each member of the structure.

First, the details of the prototype of the BRFD are presented. Second, the SC-BRFD isolator consisting of a nonlinear self-centering element and the BRFD is introduced. Finally, details of the RTHS study and the results are presented. The building's accelerations and inter-story drift from RTHS of controlled and uncontrolled cases are compared, where these cases correspond to the structure with the SC-BRFD isolator and fixed base, respectively. Results show that the SC-BRFD produces significant seismic vibration reduction of both maximum lateral floor accelerations and inter-story drifts, and reduces the damage developed in the structure during the DBE.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DAMAGE IDENTIFICATION FOR TRAIN WHEELS USING REAL TIME DATA

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[3]*The Technical University of Munich*

ABSTRACT

Train Wheel flats are commonly occurring local surface defects in railway systems, which adversely affect train ride comfort, increase fatigue risks, and raise safety concerns. The early detection of the flats is crucial for decision makers and stakeholders. Despite extensive research on wheel flat detection using various monitoring systems, accurately quantifying wheel flats without disrupting railway operations remains a challenge. In our research, we present a model-based method to quantify the size of wheel flats with real time data. A two-step important-point-selection approach is proposed for interpreting time series data. Important data points are those that contribute to the overall shape of the time series and provide information for identifying flat sizes. The proposed approach initially extracts perceptually important points that align with the human visual identification process to represent the time series shape. These points are then further filtered using joint entropy as an information-gain metric. The proposed methodology has been successfully applied to a field test conducted in Singapore, where the identified flat sizes align with the observed range of true values.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYTICAL AND EXPERIMENTAL TESTING FOR INCREASED SHEAR PLANE OF DEPLOYABLE GEOSYSTEMS FOR COASTAL STABILIZATION

Elizabeth Capretta[1], Khuzaima Hummad[1] and Ann Sychertz[1]*

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ABSTRACT

Underground deployable structures offer innovative solutions for coastal stabilization, addressing the growing challenge of soil instability in coastal areas exacerbated by shifting climates. Traditional soil stabilization methods frequently employ cylindrical piles, designed based on the interaction between the piles' surface area and the soil. A novel design for deployable geosystems presents a solution that uses less material to achieve an equivalent surface area when compared to traditional cylindrical piles. The installation process for these geosystems is torque-driven, like that of drilled shafts, rather than using impact or vibration hammers.

This paper presents an experimental methodology to determine the increase in the shear plane in sandy soil using deployable underground geosystems. Image tracking of the ink spread in sandy soil is used to determine the location of the shear plane in the sandy soil due to the torque-driven deployment of the awns of the geosystems. Furthermore, a method is described for performing a structural analysis on the geosystem, employing form-finding methods. The analysis involves creating an equivalent bar and hinge model of the awns, considering both in-plane and out-of-plane loading scenarios. By investigating the internal force distribution of the deployable awns, this structural analysis can contribute to the design of more efficient geosystems.

The findings of this study are that the ink spread tracking technique in sandy soil is useful for experimentally determining the shear plane effects of deployable awns from the geosystem, and that the bar cross-section optimization adequately represents the behavior of thick origami as it pertains to awns under in-plane and out-of-plane loading. These insights are significant advancements for understanding the optimal design and functionality of deployable underground geosystems.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MITIGATING VORTEX-INDUCED VIBRATIONS IN OFFSHORE STRUCTURES THROUGH METAMATERIAL-BASED CONTROL

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ABSTRACT

The concept of the "classical wave spectral gap" initially introduced in the context of electromagnetic waves, and known as "photonic band gap", has been subsequently extended to elastic waves. Specifically, it has been developed to achieve the complete attenuation of sound in a specific frequency range through a pronounced periodic modulation of the density and/or velocity of sound. This modulation creates spectral gaps that prevent the propagation of waves [1]. Subsequent studies concerning apparently rigid macroscopic bodies [2] have highlighted that, due to the vibration of internal masses in metamaterials, the motion of rigid material can be explained by Newton's second law only if the mass is replaced by the effective mass, a non-local operator. These studies reveal the possibility of obtaining a negative effective mass in composite materials with carefully designed microstructures, which can also consist of simple mass-spring systems called resonators. In this work, consolidated concepts of metamaterials are integrated into the dynamics of a system representing vortex-induced vibrations, aiming to generate specific gaps in the frequency response. This approach has the potential to mitigate structural vibrations in offshore structures caused by vortex shedding and potentially vibrations from other sources such as seismic or wave excitation. The current work includes numerical simulations to assess the effectiveness of the proposed method.

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Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DROPLET IMPACT ON GRANULAR MATERIAL MODELLED BY COUPLED LBM-DEM

Linlin Fei[1], *Dominique Derome*[2] *and Jan Carmeliet**[1]

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ABSTRACT

What happens when a rain droplet falls on a dry sandy beach or on a pool of mud? Droplets impacting deformable porous substrates such as sand may lead to cratering, rearrangement of the particles and mixing of droplet and substrate. Possible applications are land sliding or mud avalanches by rain erosion, soil erosion by rainstorms, control of spray irrigation, among others.

In this presentation, we propose a numerical model to simulate such problems, coupling lattice Boltzmann and discrete element methods (LBM-DEM) [1]. A cascaded LBM is used to simulate the liquid-gas flow field using a pseudopotential interaction model for describing the liquid-gas multiphase behaviour. A classical DEM resorting to fictitious overlaps between the particles is used to simulate the multi-particle system. A multiphase fluid-solid two-way coupling algorithm between LBM and DEM is constructed. The model is validated by three benchmarks: (i) single cylinder particle sedimentation, (ii) single floating particle on a liquid-gas interface and (iii) self-assembly of three particles on a liquid-gas interface. Our simulations agree well with theoretical or numerical results reported in the literature.

Our proposed model is applied to simulate droplet impact on deformable granular porous media at pore scale. The dynamic droplet spreading process, the deformation of the porous media (composed of up to 1000 solid particles), as well as the invasion of the liquid into the pores within a wide range of impact Weber number are well captured. The droplet spreading dynamics on particles is compared to droplet impact on a flat solid surface. A scaling analysis is conducted to unify the two impact problems taking into account different fluid properties (viscosity), fluid-solid interaction (surface tension) and deformability of the substrate. An energy analysis allows to determine the different mechanisms at play, showing the effects of kinetic and potential energy, surface energy and viscous dissipation.

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Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

USING HUMAN EXPERIENCE TO INTERACTIVELY REDUCE SUPPORT MATERIAL IN TOPOLOGY-OPTIMIZED STRUCTURES

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[1]Massachusetts Institute of Technology

ABSTRACT

Recent advances in additive manufacturing have created a need for new design methods to leverage the increasingly complex manufacturing opportunities. In this context, the exploratory power of topology optimization has proved capable of identifying design solutions that significantly outperform conventional low-weight designs. In topology optimization, the design problem is formulated as a formal optimization problem and solved using a mathematical program. The design is thus driven exclusively by a machine. Input by a human is only needed to initialize the design and judge the quality of the final output. Consequently, the design problem formulation must include all physics related to the design's operation and relevant fabrication constraints. This often results in complex and nonlinear design spaces where solving with gradient-based optimizers demands high iteration counts and experience in setting of parameters that land in a well-performing local minimum.

This talk discusses a new topology optimization approach in which humans and machines make collaborative design decisions. The new Human-Informed Topology Optimization framework enables improved identification of the so-called 'everyday' and 'in-the-field' design situations. The framework is based on standard density-based [1] compliance minimization with Heaviside projection [2], and MMA [3] as the gradient-based optimizer. However, the design engineer can actively use their experience to locally alter the minimum and maximum feature size requirements or impose similarity to desired drawn topological patterns. The latter is done by implementing a local appearance constraint [4]. The new approach only takes ~10 minutes to generate optimized designs and is demonstrated on several 2D and 3D benchmark examples. Leveraging human experience is shown to improve several complex mechanical performance metrics, including buckling, stress concentrations, and energy absorption. The new human-machine framework is additionally shown to improve additive manufacturability by reducing the quantity of required support material.

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DESIGN FRAMEWORK FOR MICROSCALE 3D WOVEN ARCHITECTED MATERIALS

Molly Carton[1], James Surjadi[1], Bastien Aymon[1] and Carlos Portela[1]*

[1]Massachusetts Institute of Technology

ABSTRACT

The development and realization of increasingly complex microscale architected materials has been made possible in recent years by the expanding capabilities and scales available with additive manufacturing. Expanding beyond the paradigm of stiff beam and shell-based lattices, we have drawn inspiration from the fiber-based hierarchy of weaving and the entanglement of biological polymers like collagen to produce a tailorable 3D woven architected material that demonstrates fabric-like deformation, expressing topology-dependent entanglement leading to high compliance and exceptional extensibility. However, the potential of these architectures has been limited by reliance on manual design tools, so that previous work has only been able to study two of the possible architectures within this paradigm. Within this mostly untapped property space, spatially variable compliant micro- and nano-scale features could advance applications such as tissue engineering where 3D porosity and tunable mechanical properties are desirable.

Here, we provide a computational design framework for these woven architected materials that allows for spatial variation of fiber- and lattice-level parameters, allowing rapid generation of functionally graded architectures that can be fabricated at the micron scale. Variation of parameters at the sub-unit-cell level (on individual truss elements) greatly extends the design space and facilitates new modeling methods for these novel architectures. This work uses the strategy of reducing the lattice to a graph representation in order to create the weave topology, enabling the creation of woven materials with complex yet tailorable mechanical responses. We introduce design rules for these self-entangled structures and use these rules to produce alternate topologies and functionally graded structures. We rapidly evaluate structure-property relations for this expanded design space using scripted finite element modeling, and we validate this work by fabricating these structures using two-photon lithography and performing in-situ large-strain tension experiments, demonstrating the expanded property space made available by this design framework.

COMPREHENSIVE NUMERICAL STUDY OF THE UNCERTAINTIES OF HUMAN-STRUCTURE INTERACTION ON FOOTBRIDGES

Bryan Castillo[1], Johannio Marulanda[1], Albert R. Ortiz[1], Peter Thomson[1] and Lauren Linderman[2]*

[1]Universidad del Valle
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ABSTRACT

The technical and aesthetic requirements addressed in recent urban regeneration, coupled with the incorporation and progressive development of more resilient and lightweight materials, have rendered civil structures, particularly footbridges, susceptible to excessive vibrations due to interaction with dynamic loads. This susceptibility is particularly evident given their role in serving loads induced by human walking. These loads exhibit interrelation phenomena with structural vibrations, and vice versa, brought about by coupling effects commonly referred to as Human-Structure Interaction (HSI). Two primary aspects are considered in the study of HSI effects: the alteration of dynamic properties in the structure due to the additional presence of non-stationary mass and damping, and the degree of coupling between pedestrians in transit, as well as between pedestrians and the structure. The conditions of the HSI in footbridges constitute a precise phenomenon, where the propagation of uncertainties in analytical models, for their representation, allows for the consideration of some extent of the variability in the dynamic condition and non-stationary nature of these anthropic loads. This study focuses on the intrinsic uncertainty propagated by human walking and its dynamic effects on the response of a numerical model of a reference pedestrian bridge. Pedestrian-induced loads were simulated using the equation proposed in international reference guides with 10.0% variability in the step frequency and walking phase. Simultaneously, the reference structure was modeled based on a fourth-order partial differential equation (PDE) with external disturbances. Finally, the effects of HSI were estimated by coupling anthropic solicitations to the structure and determining its response, compared with the static and dynamic reference limits.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMPLEMENTATION OF A HYBRID ACTIVE-PASSIVE MULTI-STAGE FLOW CONTROL SYSTEM IN A LARGE BOUNDARY LAYER WIND TUNNEL FOR THE PHYSICAL SIMULATION OF NEAR-SURFACE EXTREME WIND PHENOMENA

Ryan Catarelli[1], Yutiwadee Pinyochotiwong[1], Forrest Masters[1], Brian Phillips[1], Tai-An Chen[1], Jennifer Bridge[1] and Kurtis Gurley[1]*

[1]*University of Florida*

ABSTRACT

This work presents the implementation of an automated multi-stage flow control system in a large boundary layer wind tunnel (BLWT) designed and fabricated at the University of Florida (UF) Experimental Facility within the NSF Natural Hazards Engineering Research Infrastructure (NHERI) program. The goal is to advance the reduced-scale physical simulation of a variety of complex near-surface turbulent flows observed in the field. The most significant challenges in reproducing near-surface wind fields in the traditional BLWT are simulating low-frequency turbulent content and/or nonstationary wind characteristics known to be embedded in most extreme wind events. These characteristics may affect the separation zones on model structures and introduce errors in the estimation of peak wind loading.

Generating the necessary low-frequency and/or evolutionary spectral content at model-scale requires physical simulation equipment capable of rapidly modulating wind speed and turbulence characteristics to achieve kinematic similitude with full-scale wind phenomena. To achieve this, the first stage—a bank of vaneaxial fans (VAF)—drives the overall mass flow in the tunnel and enables coarse velocity profile shape control. Turbulence is synthetically generated and injected into the flow using the second stage—a multi-fan array called the Flow Field Modulator (FFM). The FFM produces rapid velocity changes and enables fine control of profile shapes. High-frequency near-surface energy content is modified via the third stage—an automated roughness grid called the Terraformer (TF). The VAF and TF are adjustable passive devices—they are configured prior to testing and remain at steady-state during a test. The FFM can be used as an adjustable passive device or as a controllable active device depending on the simulation target. A governing convergence algorithm (GCA) is employed to adjust the control inputs to the VAF, FFM, and TF until the target flow conditions are achieved. The three stages coordinated by the GCA comprise the combined hybrid active-passive flow control system.

Simulation targets in this study were generated for a range of flow conditions in the BLWT including stationary and nonstationary non-monotonic profile flows and stationary low-frequency turbulence control. The ultimate goal for this system is to reproduce the relevant characteristics of time-varying non-synoptic flow fields either as observed in field data, described by analytical models, or modeled by computational fluid dynamics. The presentation will also more broadly discuss the high-throughput measurement tools in the UF BLWT that are accelerating the rate of experimental discovery, a necessary capability for achieving arbitrary target transient flows.

ENHANCING ELECTRICITY RESILIENCE THROUGH ROOFTOP PANELS AND BEHIND-THE-METER BATTERIES FOR COMMUNITIES EXPOSED TO HURRICANES

Luis Ceferino[1], Ning Lin[2] and Prateek Arora[3]*

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ABSTRACT

Projections indicate that solar energy will constitute 55% of total electricity capacity by 2050 in the US, with a large share in the form of residential rooftop panels. These panels can generate electricity locally at the household level, reducing communities' reliance on vulnerable and old distribution lines for electricity access during extreme events, like hurricanes, which often trigger significant outages, e.g., Hurricane Ian (2022) with 2.6 M outages. Despite solar energy's growing importance for resilience, few studies have analyzed the risks of countrywide deployments of solar infrastructure due to extreme weather events. This presentation will summarize a new probabilistic framework to quantify electricity access in households with rooftop panels and behind-the-meter batteries during hurricanes. We integrate data-driven models that capture two critical and compounding factors that dominate solar generation during hurricanes: transient cloud conditions that decrease irradiance and high winds that can cause permanent panel damage. We also couple our proposed framework for solar panels with a probabilistic model that predicts outages due to damage to the traditional grid's components (e.g., distribution lines) to quantify the added benefits of solar panels and behind-the-meter batteries for electricity access during emergencies. We will present case studies at different spatial scales ranging from regional levels in the Eastern United States to the community levels for neighborhoods in New Jersey. These methods and applications show how risk assessments for power systems can help policymakers and utility companies design clean energy investments that enhance electricity resilience to protect the most vulnerable communities from extreme events.

TOWARDS CLIMATE RESILIENCE: EVALUATING THE MITIGATIVE IMPACT OF STRENGTHENING RESIDENTIAL BUILDINGS ON HURRICANE RISKS

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ABSTRACT

Hurricanes are one of the biggest natural hazards, causing widespread and severe physical damage to buildings. Hurricane risks are projected to exacerbate under climate change. As the worsening effect of climate change on hurricane risks has been suggested by many studies, the urge to protect buildings from hurricane damage has been rising, resulting in studies on the general strategies to lower the future hurricane risk through a direct building code change and the specific mitigation strategies to strengthen the buildings' load carrying components. Due to the slow pace of building code updates, the low adoption rates of these codes, and their emphasis on new constructions, representing only a small fraction of the total building inventory, prioritizing changes on building code will have a limited hurricane risk reduction impact on the entire building inventory. Implementing specific mitigation strategies to strengthen building components could offer a practical way to protect both the new and existing buildings from increasing hurricane risks. Therefore, this study aims to conduct a comprehensive risk assessment essential for adopting strategies to strengthen building components. We investigate the hurricane risk mitigation benefits of installing add-on structural components (accordion windows, perforated parapets, and hurricane clips) in terms of to what extent they can reduce hurricane losses at the building inventory level. A predictive building composition model, which features maintenance, construction, and demolition of buildings, and the risk mitigation implementation timing, to project future building inventory considering the hurricane mitigation strategies is proposed in this study. Also, an Artificial Neural Network to estimate aggregated regional loss based on hurricane parameters and building inventory is developed and used to efficiently conduct hurricane risk assessment on 8 southeastern states in the U.S. at the Census tract level. Model projections suggest that across all study regions, between 32.11% and 44.58% of existing buildings are expected to be replaced with mitigation-enhanced new structures by 2055. These rates increase to between 77.30% and 89.56% when a 5% maintenance of existing buildings is applied. By 2100, without considering maintenance, the replacement and construction percentage is anticipated to range from 72.50% to 77.55%, and with maintenance, it is projected to exceed 99%. The risk assessment results indicate that the average annual insured loss reduction is estimated to range from approximately $90,000 to $214,000 per county under RCP 8.5 climate conditions for the considered periods, 2040-2050 and 2090-2100, which increase with maintenance.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCED REAL-TIME FORCE CONTROL AND ITS APPLICATION TO THE SEISMIC PERFORMANCE EVALUATION OF BASE ISOLATION BEARINGS

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ABSTRACT

The lateral response of base isolation bearings such as friction pendulum bearings (FPB) and lead rubber bearings (LRB) is sensitive to the axial force applied to the bearings. Therefore, during experimental tests, it is crucial to maintain well-controlled axial forces to reliably assess the seismic performance of these bearings. In the past, accurately controlling the axial force on the bearings using servo-hydraulic actuators in real-time posed challenges due to the highly sensitive response of force control, especially with axially stiff bearings. Recently, a new real-time force control algorithm (Cho et al. 2023) was developed based on the existing D-ATS force control method (Chae et al. 2018). This method can incorporate the velocity and force change rate feedbacks into the control loop, without using any additional sensors beyond the default sensors given in a typical servo-hydraulic actuator (e.g., displacement and force sensors), which is beneficial to improve the force control accuracy. With this method, characterization tests for LRBs and FPBs can be conducted with well-controlled constant and time-varying axial forces. Additionally, real-time hybrid simulations for base-isolated structures equipped with these bearings and subjected to both horizontal and vertical ground motions can be carried out. This study will present and discuss the experimental test results.

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Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GENERATIVE WAVELET NEURAL OPERATOR FOR SCIENTIFIC MACHINE LEARNING

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ABSTRACT

Neural operators have evolved to be an effective scientific machine learning tool for efficient and reliable prediction of dynamic evolution of dynamical systems for unseen future events. Concurrently diffusion models have also attracted a large number of interests from the scientific community for generative (e.g., image generation, image-to-image translation) and discriminative tasks (e.g., image segmentation, anomaly detection, classification). In this work, we integrate the generalizing capability of neural operators with the generative property of diffusion models and propose the diffusion neural operator for uncertainty quantification in scientific machine learning. In particular, we employ the recently proposed wavelet neural operator for learning the data distribution. The use of the wavelet neural operator in the diffusion model increases the ability to learn strong latent representations of underlying observations, allowing to capture the probability distributions accurately. The learned probability distributions allow for the quantification of uncertainty by providing a range of possible outcomes and their associated probabilities. This is valuable for exploring the complete uncertainty space and generating samples for various scenarios, thereby enabling reliable estimates of uncertainty in future predictions, and helping decision-makers understand the range of possible outcomes and associated risks. We believe, the proposed diffusion neural operator framework will be particularly useful in fields such as engineering, finance, medical imaging, and climate modeling, where both accurate predictions and understanding of uncertainties are crucial for decision-making.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF STRUCTURES MADE OF PRINTING-DRIVEN ANISOTROPIC MATERIAL RESPONSE CONSIDERING STRENGTH AND SERVICEABILITY REQUIREMENTS

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ABSTRACT

Construction 3D printing has emerged as a dynamic and rapidly advancing research field, fueled by its promising ability to revolutionize construction processes by offering a multitude of advantages in construction that can transform traditional engineering practices, such as by automating the design and building process. Out of the various materials that have been used for printing, concrete 3D printing has been receiving growing attention in the realm of structural engineering applications. Unlike bulk concrete which is practically an isotropic material, concrete 3D printing produces a layered macrostructure with different properties in three major directions. Because printing can be performed in different directions, a reasonable question that arises is: Can we optimize printed structures with respect to their layer-to-layer interface orientation as well as their material distribution, while simultaneously criterial relating to strength and serviceability requirements are satisfied? To address this question, this study formulates a density-based topology optimization framework that minimizes the structure’s weight with respect to both the material distribution and layer-to-layer interface orientation under stress and displacement constraints. Stress constraints represent strength design requirements and displacement constraints represent serviceability requirements. The printed concrete is treated as a homogeneous orthotropic material. The stress constraints adopt the Liu–Huang–Stout yield criterion, which is an extension of the Drucker–Prager yield criterion to anisotropic materials. Both the elasticity tensor and the yield criteria are expressed in the local material coordinate system that varies during the optimization process. Also, both the stress and the displacement constraints are expressed as local constraints. To achieve computational efficiency, the Augmented Lagrangian approach together with the Method of Moving Asymptotes has been implemented, while all derivatives/sensitivities are calculated using the adjoint method, which significantly reduces computational cost. Various details of the proposed optimization framework will be discussed including various forms (and scaling) of the stress constraints, which has been investigated as a means of accelerating convergence. This topology optimization framework is used to optimize various structures under fixed and free layer orientation. Preliminary observations show that free layer orientation results in lighter structures as compared to designs under fixed layer orientation.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL HEALTH MONITORING FOR RISK ASSESSMENT AND RELIABILITY OF A BRIDGE AFTER AN EXTREME LOADING LIKE EARTHQUAKE

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ABSTRACT

The present paper is focusses on the latest health monitoring techniques and system for continuous health assessment and reliability of a bridge especially after an extreme forces like earthquake. The Indian bridges are deteriorating due to harsh environmental condition, over traffic and some natural disaster like earthquake. It is very essential to timely monitor the heath of a bridge structure in such aggressive environmental conditions in terms of retrofitting or rehabilitation of a bridge and also the reliability for the remaining useful life of a structure. All available Global and Local techniques for structural health monitoring were studied. Among these techniques the Electro-Mechanical Impedance technique is found very sensitive to incipient damage detection. The EMI technique is a relatively new technique of structural health monitoring in which a PZT patch is bonded to the surface of structure using high strength epoxy adhesive or embedded in structure whose health is to be monitored. The signature of the PZT patch is acquired over a high frequency range (30-400 kHz) with the help of LCR meter or impedance analyzer. The signature is complex in nature, Detection of incipient damage is quite critical and challenging task for health monitoring of structures with traditionally available techniques. In this study, through artificial damage created in the Bridge and it is found that the incipient level damage is very quickly detected by the EMI technique. The proposed EMI technique is considered as most reliable health monitoring technique for Indian bridges.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS-INFORMED NEURAL NETWORKS TO SOLVE INVERSE PROBLEMS IN HETEROGENOUS ELASTIC MEDIA

Abhisek Chanda[1], Dibakar Roy Sarkar[1], Chandrasekhar Annavarapu[1] and Pratanu Roy[2]*

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ABSTRACT

Inverse problems in engineering comprise the challenge of deducing the material parameters, external boundary conditions, and concealed physical phenomena by analyzing data on field variables that are already known. These problems find diverse applications in geomechanics, including hydrocarbon extraction, geological carbon storage, reservoir stimulation, and more. In the context of geomechanics, tackling inverse problems involves the fundamental task of identifying interface geometry along with determination of material properties, considering the prominent heterogeneity observed in the geological subsurface.

Traditional parameter identification for complex models is challenging, necessitating numerous forward simulations, which vary based on model complexity and the number of parameters. Hence, these are often restricted to simplified models due to computational constraints. The advent of physics-informed neural networks (PINNs) represents a notable advancement, proving highly effective in simultaneous parameter identification and the fitting of artificial neural network models to data, showcasing promise in discovering hidden physics and efficiently handling high-dimensional challenges.

Leveraging the potency of PINNs as a powerful tool for solving inverse problems, we propose to extend the work [1-2] related to identification of material parameters with an unknown interface in the domain of mechanics of heterogenous elastic media. We propose to employ dimensionless formulation of the governing equations to reduce disparities in variable scales, preventing certain variables from dominating the model training and ensuring more consistent steps in the optimization process, resulting in faster convergence and improved overall performance. We have introduced several strategies such as imposing boundary conditions as hard constraints and random weight factorization to enhance the approximating capability of PINNs. The performance and capability of our proposed framework is showcased through numerical examples ranging from simple interface geometries, such as layered materials and circular inclusions, to complex interface geometries, such as petal shaped inclusion.

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PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING THE LONG-TERM CLIMATE IMPACT ON FLEXIBLE PAVEMENT PERFORMANCE

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ABSTRACT

Environmental factors significantly influence the functionality of flexible and rigid pavements. In the case of flexible pavement, the design process necessitates careful consideration of multiple variables such as constituent materials, traffic volume, variations in water tables, and the anticipated climatic conditions throughout the road's lifespan. The pavement design life is usually 20 years, but overlooking current and future design practices can lead to decreased performance. Integrating climate forecasts into pavement design is a complex task; however, it can provide valuable information about pavement’s lifespan under such conditions. This study assesses the impact of three distinct future climates on pavement performance and the duration required to reach failure thresholds conducted across four major locations in the State of Hawaii, the United States. AASHTOWare Mechanistic-Empirical (ME) Pavement Design was used for its flexible pavement design methodology. The Pavement ME model predicts various performance indicators, including rutting, alligator cracking, longitudinal cracking, international roughness index, and permanent deformation. Projections illustrate diverse changes in expected pavement performance across locations, yet the majority indicate a decline compared to existing design standards. The analysis highlighted the significant impacts of climate change on pavement performance, particularly in increased longitudinal cracking with higher temperatures. The predicted international roughness index remained largely unchanged across diverse climatic locations, while climate change notably impacted overall rutting and asphalt concrete rutting in the pavement. Notably, the findings underscore the significant influence of altered climatic data on pavement performance.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PRELIMINARY STUDY OF ISOLATION BEARINGS WITH DISCONTINUOUS INERTERS FOR SEISMIC PROTECTION OF ESSENTIAL EQUIPMENT AND COMPONENTS

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ABSTRACT

Earthquakes not only impact buildings but also influence essential equipment and components, such as high-precision manufacturing machines in high-tech facilities. Meanwhile, excessive earthquakes can cause enormous economic losses for the equipment and components. To prevent damage from these earthquakes, seismic isolation underneath these equipment and components is commonly applied to enhance seismic performance. In recent years, researchers found that additional inerters, along with seismic isolation, can yield better performance in reducing isolation responses. However, this combination further reduces accelerations while increasing displacements in the isolation layer. Therefore, this study aims to develop and experimentally verify seismic isolation bearings with discontinuous inerters. In this study, the mathematical model of the proposed system is established. In the phase transition, the conservation of momentum is employed. Then, this model is evaluated using the harmonic balance method to obtain the frequency response with respect to an input intensity. This frequency response provides an understanding of the effect of discontinuity compared to the isolation bearings alone and the isolation bearings fully attached with inerters. Finally, this frequency response is experimentally verified using shake table testing. In addition, historical earthquake inputs are also exploited in the experiment to evaluate the performance of the proposed isolation system. The experimental results show that the proposed isolation system can generate better performance as the input intensity increases.

Advances in vibration and structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMIZATION OF DOUBLE TUNED MASS DAMPER CONSIDERING SOIL-STRUCTURE INTERACTION EFFECT

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ABSTRACT

This study presents a methodology for optimizing double tuned mass dampers (DTMDs) positioned on the top floor of a ten-story building subjected to ground motions, taking into account soil-structure interaction (SSI). In the optimization process, double TMDs are considered to be connected both in series (STMD) and in parallel (PTMD). The equations of motion for an n-story shear building controlled by STMD and PTMD are derived, considering the SSI effect. The optimum parameters for both devices are obtained by minimizing the root mean square (RMS) of the top-floor displacement using the Particle Swarm Optimization (PSO) algorithm. For the time history analysis, ten site-specific earthquakes corresponding to Zone V (IS 1893:2016) are employed. Additionally, the influence of soil stiffness on the optimum parameters and effectiveness of PTMD and STMD is discussed. Numerical results indicate that the optimally designed PTMD and STMD effectively suppress the maximum floor displacements and accelerations of the building. It is also demonstrated that SSI effects can be ignored when the building is constructed on stiff soil. Furthermore, it is concluded that SSI and earthquake frequency content significantly affect the control performance of TMDs and the seismic response of the building.

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELECTROCHEMICAL-CHEMICAL-MECHANICAL PHASE FIELD MODEL FOR RUST PRECIPITATION-INDUCED CRACKING IN CONCRETE

Airong Chen[1], Xurui Fang[1] and Zichao Pan[1]*

[1]Tongji University

ABSTRACT

Evaluating the degradation process of concrete under corrosion-induced concrete fracture is significant in prolonging the service life of structures. This paper presents an electrochemical-chemical-mechanical phase field model to study the processes of non-uniform corrosion, reactive transport and precipitation of Fe(OH)2 and Fe(OH)3, rust precipitation -induced cracking. The non-uniform corrosion is described based on the electrochemical theory and the precipitation reactions of Fe2+ and OH- in the concrete pore are considered. The eigenstrain caused by rust is related to the volume fraction of rust. The phase field regularized cohesive zone model is calibrated for concrete cracking. The phenomenon of rust movement through cracks can be observed by relating the diffusion coefficient of rust and the phase field variable. The proposed model is validated with the experimental data and shows good agreement with the experimental data.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS OF 3D MICRO-ARCHITECTED INTERPENETRATING PHASE COMPOSITES

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ABSTRACT

The design of modern composite materials, as used in a wide range of engineering applications, is largely derived from a traditional framework based on laminates. While resulting in desirable strength and stiffness properties, the laminate-based structure leads to a high degree of anisotropy and unique failure modalities like interlaminar failure, limiting the performance of these composites under complex loading conditions. Meanwhile, recent work in the field of architected materials has yielded a thorough understanding of geometry-dependent material behavior, enabling the development of highly robust architectures with tunable (an)isotropy. However, such advances have focused primarily on describing the response of lightweight architected geometries comprised mostly of air. Consequently, the addition of a load-bearing matrix phase can alter the stress state of an architected material when placed under load; however, the composite response is not well understood.

Here we investigate the effect of geometry and constituent material properties on the mechanical performance of 3D-architected interpenetrating phase composite (IPC) materials, i.e., two-phase materials consisting of an architected structure surrounded by a matrix. Using computational homogenization, we first predict how resultant coupled stress states in the composite change with the material properties of each individual phase, contextualizing the results within the traditional stiffness scaling laws. We then demonstrate two robust fabrication pathways for realizing centimeter-scale architected IPCs with micro-scale features, via vat photopolymerization 3D printing followed by pyrolysis or via two-photon lithography 3D printing, each followed by matrix infiltration. Using these prototypes, we study the mechanical behavior of the fabricated composites under uniaxial compression, with particular emphasis on the non-linear and failure regimes. We show that independent of the material system, the presence of a load-bearing matrix distributes the stress in the composite, contributing to a high-strength, globally stretching-dominated failure behavior, regardless of nodal connectivity. Moreover, the development of a 3D, highly tortuous pathway for stress delays or prevents catastrophic failure of the traditionally brittle architecture phase, resulting in energy dissipation performance of the composite that exceeds the sum of its individual constituents. Altogether, this work broadens our established understanding of the link between architecture and mechanical performance by considering the framework of interpenetrating phase composites, creating the foundation for a new class of strong, resilient, and programmable architected materials.

Toward data-driven approaches for uncertainty quantification and propagation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN STOCHASTIC CONSTITUTIVE MODEL FOR STRUCTURAL ANALYSIS

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ABSTRACT

It is vital to guarantee the reliability and safety of the structure to understand the stochastic mechanical behaviors of the construction materials. However, the random behaviors of the materials are usually hard to be mathematically described, especially those new materials. In order to quantify the uncertain material behaviors, a data-driven model, called Gaussian process regression, is employed in this study. The developed data-driven model is validated by both elastic and plastic experimental data first, and then the associated formwork is established to incorporate the data-driven stochastic constitutive model for structural analysis and reliability analysis. The correlation between different material behaviors is also encoded into the data-driven model by using the proper orthogonal decomposition. The high accuracy is evidenced in the numerical examples. In addition, the developed data-driven model is used to describe the stochastic constitutive behavior of the additive manufactured parts as well, and is hybridized with the genetic algorithm to optimize the 3D printing process parameters for better performance.

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VERTICAL EARTHQUAKE EFFECTS ON COLUMN AXIAL RESPONSE IN TALL CORE-WALL BUILDINGS

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ABSTRACT

In tall reinforced concrete buildings, the columns commonly carry high axial loads and are of special interest when considering the combined effects of horizontal and vertical earthquake ground motions. A common configuration for tall reinforced concrete buildings consists of a centrally located reinforced concrete core wall surrounded by flat plates and perimeter columns. Under lateral loads, the slab-column gravity framing acts as an outrigger for the core walls, causing an increase in the axial forces in the columns due to the overturning moment resistance provided by the gravity system. The vertical vibrational periods of a tall reinforced concrete building are likely to coincide with the short-period amplification range of vertical ground motions, which may result in increased column axial forces. This study examined the response of columns in a tall reinforced concrete building under the combined effects of vertical ground motions and outrigger action of the gravity system under horizontal ground motions. An archetypal core-wall building with 40 stories was designed to obtain a representative example of building response, and a nonlinear finite element model was developed to represent a slice from the building plan. Nonlinear response history analysis was performed using a suite of ground motion records at the Maximum Considered Earthquake level with both the horizontal and vertical components of motion. Results are compared with current building code provisions for vertical ground motions, and design recommendations are provided.

Machine learning applications in wind engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AI-BASED RECOGNITION FOR WIND DAMAGE INDICATORS: A COMPREHENSIVE APPROACH

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ABSTRACT

KEYWORDS: Damage Assessment, Object Detection, Wind Damage, Deep Learning

ABSTRACT

The impact of wind hazards have become increasingly severe. Understanding the magnitude of the hazard is crucial for hazard mitigation and community resilience. Given the challenges to deploy in-situ measurements for the extreme wind hazards (such as tornadoes and hurricanes), post-damage data is commonly the focus. To estimate hazard magnitudes, wind damage indicators are typically raised, such as building, tree, sign pole and debris. A significant gap exists between the manual collected damage data (such as images, aerial photos, or videos of the damaged buildings, snapped trees, debris) and the attribute values of the wind damage indicators (such as location coordinates, size, and orientation). Hence, the automating precise object detection is needed for this limitation.

This study introduces an innovative workflow that relies on cutting-edge deep learning models to approach the versatile recognition for wind damage indicator. Firstly, the workflow enhances the annotation capabilities of the post-damage dataset by Transformers (Vaswani et al. 2017) in Computer Vision (ViT). ViT is benefited by self-attention mechanisms and allow the model to capture long-range dependencies in the input data for understanding global context. The post-damage dataset can then be categorized by the damage severity and indicator types. Then, automated ROI detections can be used for color-based detection, edge detection or R-CNN based on the complexities for each category to obtain the attribute values of the objects.

Utilizing example datasets from the as Texas and Louisiana March 2022 Tornado Outbreak Event, 2023 Kentucky Tornado and Hurricane Harvey, this comprehensive approach achieves accurate segmentation of wind damage indicators through fine-tuning ViT and ROI detection. This versatile recognition approach marks a transformative step in wind hazard post-damage assessment and provide a powerful tool for obtaining wind field information from indirect observation data.

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Molecular scale modeling and experimentation

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PREDICTIVE MODELING OF MECHANICAL BEHAVIOR OF CRUMPLED SHEETS

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ABSTRACT

Crumpled nanosheet with structural defects lead to intriguing mechanical properties compared to pristine systems. In this work, different machine learning algorithms and artificial neural network (ANN) structures are utilized to predict the mechanical properties of crumpled nanosheet under various impact factors of structure size, Stone-Wales (SW) defect, and compaction ratio. The predictions include bulk modulus, hardness, and effective modulus. The coarse-grain molecular dynamics (CG-MD) simulations were conducted to generate the training dataset. It was discovered that SW defect has positive effects on mechanical properties while compaction ratio has negative correlations. Regarding structure size, a negative correlation was observed with bulk modulus and hardness, whereas a positive relationship was noted with the effective modulus. Interestingly, the stochastic gradient descent (SGD) method demonstrated limitations in capturing the nuanced effects of these varying factors on the mechanical properties of crumpled nanosheet, while decision tree (DT), support vector machine (SVM), k-nearest neighbors (KNN) and ANN yielded more accurate and desirable predictions. Discoveries in this work provide new perspectives to the understanding of nanoscale mechanical properties, leveraging advanced computational techniques.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATED ORIGAMI AND TENSEGRITY SYSTEMS DYNAMICS BASED ON THE BAR-HINGE MODEL

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ABSTRACT

Origami and Tensegrity stand as the two prominent paradigms in advanced deployable structures, their design principles rooted in both biological systems and artistic concepts. Origami, observed in natural formations like flowers, lobster tails, and fish fins, is renowned for enabling complex shapes, ensuring compact storage, facilitating cost-effective production, and providing tunable properties in metamaterials. Despite these advantages, origami structures typically exhibit low stiffness and challenges in controlling transient dynamics. Conversely, Tensegrity, evident in biological structures such as cells, elbows, and spider webs, is characterized by mass efficiency and robust energy absorption capabilities. Its primary challenges lie in the complex fabrication of joint structures and the lack of a cover for the bar-string network.

This study presents an explicit form of the dynamics of origami and tensegrity systems as a cohesive whole based on the Finite Element Method (FEM). By conceptualizing origami components as a bar-hinge model and defining the system's generalized coordinates as nodal coordinates and hinge angle vectors, this study derives a comprehensive mathematical framework of the system's nonlinear dynamics, with and without constraints, using the Lagrangian method. By neglecting the time derivatives of the dynamics, the equilibrium and compatibility equations are further included. We lay out linearized dynamics and modal analysis equations using Taylor's expansion theory. This approach enables extensive dynamics investigations for integrated origami and tensegrity systems, encompassing FEM dynamics simulations across various conditions, modal analysis for natural frequencies and modes, and large deformation analysis to understand stress distributions and actuation strategies. We also introduce a structural control framework via a precise linear state-space model. The practical application of these theories is demonstrated through two aerospace examples: a deployable solar panel and a shade cover for space telescopes, both rigorously analyzed and compared with static analysis. Ultimately, this study not only enriches our understanding of structural and material properties but also significantly advances the design and construction of deployable structures, leveraging the synergistic integration of origami and tensegrity principles to address complex engineering challenges.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REVOLUTIONARY EXPANDABLE ROTATING SHIELDED SPACE HABITAT: PIONEERING SUSTAINABLE LIFE BEYOND EARTH

Anthony Longman[1] and Muhao Chen[2]*

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[2]University of Kentucky

ABSTRACT

The proposed rotating habitat is an innovative venture designed to create sustainable, Earth-like environments in space. This structure, beginning as a compact cylinder, is engineered for periodic expansions, ultimately housing up to 8,000 people and featuring a rich interior ecosystem with lakes and 10,000 trees. Its economic viability stems from a self-sustaining model from day one, with gradual expansions reducing the costs associated with large-scale space constructions. Central to this habitat's design is a growth architecture based on repeated self-similar steps, ensuring scalability and adaptability. This strategy positions the habitat as a key player in asteroid and lunar mining and as a primary market in this sector. The rotation rate, initially 4 rpm and decreasing to 2 rpm at full expansion, will result in an effective simulation of Earth's gravity, fostering a comfortable environment for its inhabitants.

This design concept is informed by over six decades of human spaceflight data, emphasizing the necessity of Earth's gravity for human physiology. The gradual expansion of the habitat allows for replicating Earth's gravitational conditions, essential for long-term human habitation in space. This approach circumvents the challenges of constructing large-radius structures simultaneously, maintaining functionality throughout the expansion process. The habitat features a substantial interior volume and a self-sufficient life support system, essential for long-term space habitation and continuous interaction with a 'living' environment. Its rotating seed structure supports these expansions, and an innovative microgravity industrial zone is integrated along the central axis, expandable without impacting the habitat's overall quality.

Economically, this habitat transforms the concept of space living, making it more accessible. It provides gravity, radiation protection, sustainable food sources, and significant open spaces for human comfort. The rotational speed is maintained at a maximum of 4 rpm to ensure a comfortable gravity gradient for the well-being of inhabitants. A unique feature of the habitat is its capacity to offer varied gravitational environments, enhancing plant growth and facilitating human health studies under different gravity levels. This design also fosters commercial opportunities in manufacturing and operating in selectable gravity environments. In sum, this rotating habitat combines human-centric design with economic viability and ecological sustainability, marking a pivotal step in humanity's journey of space exploration and long-term living beyond Earth.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACTIVE INERTER DAMPER SYSTEM: CONTROL SYNTHESIS, FORCE TRACKING, AND EXPERIMENTAL VALIDATION

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ABSTRACT

A novel active control device named active inerter damper (AID) has been proposed and verified to mitigate seismic response of buildings. The AID system is composed of a mechanical inerter, a servo-hydraulic actuator, sensors, and a digital controller. The AID system has a compact size and light-weight design, owing to the mechanical properties of the inerter that amplify the inertial force by several times the mass of the inerter. Consequently, the installation of an AID system is cost-effective in practical engineering applications. This study first proposed, designed, and validated two force tracking controllers for the AID system in the structural laboratory as the force tracking performance of an active control system is crucial for its seismic control effectiveness. Subsequently, shake table tests were conducted on a three-story steel specimen with an AID system to verify the feasibility of AID control application for buildings. The control force was computed using a ma-chine learning-based controller that directly utilized acceleration measurements feedback from the steel specimen. Experimental results demonstrate that the seismic response of the steel specimen was reduced effectively. Finally, this study employed real-time hybrid simulation (RTHS) to assess the control performance of the AID system installed on a 10-story shear building. The AID was physically tested while the shear building was numerically simulated. Three approaches for acquiring the achieved force of the AID were proposed and applied to the RTHS. Experimental results show that the AID system successfully and efficiently reduced the seismic response of the 10-story building.

DISCRETE ELEMENT MODELING OF FLEXIBLE GRANULAR MATERIALS – FROM CONTACT MODELS TO PARTICLE FLOW SIMULATIONS

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ABSTRACT

Granular materials, such as geomaterials (e.g., sands, gravels, extraterrestrial regolith), biomass feedstocks (e.g., wood chips, switchgrass), are ubiquitous in nature and in engineering applications. In this presentation, we report recent advancements in modeling flexible granular materials, specifically biomass materials. We have first proposed a set of hysteretic nonlinear contact models for approximating the bulk strain-hardening phenomena of relatively soft granular materials. These contact models comprise of simple polynomial and/or exponential functions to allow for easy calibration. To ensure numerical stability, we have derived unconditionally stabilized viscous damping force models. The resultant DEM model is implemented in LIGGGHTS-INL and applied to simulate an axial compressibility test and hopper flow for milled pine chips. Results show that the DEM model can reproduce the bulk stress–strain profiles of the physical samples and that the predicted responses agree reasonably with the experimental data.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RANDOM VIBRATION ANALYSIS OF MAGLEV VEHICLE-BRIDGE COUPLED SYSTEMS WITH NONLINEAR ELECTROMAGNETIC FORCE USING EQUIVALENT LINEARIZATION - EXPLICIT TIME DOMAIN METHOD

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ABSTRACT

Safety issues related to maglev vehicles running on viaducts excited by earthquakes need to be taken into consideration in the design of high-speed maglev line. However, the use of linearized electromagnetic force by Taylor series expansion may fail to characterize the random seismic responses of the vehicle and the bridge subsystem. This study is devoted to random vibration analysis of maglev vehicle-bridge coupled systems with nonlinear electromagnetic force considering random seismic excitation and guideway irregularity using the equivalent linearization - explicit time domain method (EL-ETDM). In the frame of equivalent linearization method, the original nonlinear random vibration problem is transformed to the random vibration analysis of the coupled systems with equivalent linear electromagnetic force. The explicit expressions of the equivalent linear electromagnetic force and the equivalent linear system responses are constructed in terms of the ground acceleration and the guideway irregularity by virtue of the dimensional-reduced formulation capability of ETDM. An efficient iterative scheme is then proposed for solving the equivalent linear random vibration problem, since the equivalent coefficients for the linearized electromagnetic force depend on the to-be-determined statistical moments of system responses. Two numerical examples, including a 2-degree-of-freedom maglev vehicle and a 3-car maglev train traversing a multi-span simply-supported bridge, are presented to demonstrate the efficacy of EL-ETDM for stochastic dynamic analysis of maglev vehicle-bridge coupled systems under the combined action of random seismic excitation and guideway irregularity.

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Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WHEN TRANSFER LEARNING MEET LOW-RANK DICTIONARY LEARNING: A FAST CRACK DETECTION METHOD IN SHM

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ABSTRACT

Existing image-based crack detection methods, especially deep learning-based methods, have been actively explored in recent years. However, it usually takes a few hours or days to train a network, with the use of high-performance computing systems. To reduce the computational burden, this study presents a novel crack detection method with a combination of transfer learning and dictionary learning. First, it reused a well-known deep convolutional neural network (ResNet18) pretrained on another dataset, and “transferred” its learning ability to our crack detection task. Based on the transferred features, a new classifier was then generated for crack recognition via low-rank dictionary learning. Due to the already extracted features and limited parameters in the dictionary learning, the training time and required labeled images decreased dramatically. The method outperforms existing deep learning approaches in accuracy and computation time, making it a promising tool for real-time crack detection on computationally limited platforms, such as battery-powered unmanned aerial vehicles.

ALGORITHMIC DESIGNS OF ARCHITECTED MATERIALS WITH COMPLEX MICROSTRUCTURES

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ABSTRACT

We focus on designing architected materials that exhibit target non-linear stress-strain responses. First, we highlight the challenges in designing architected materials for large deformations. Given the unbounded complexity in a generalized algorithm, we instead demonstrate two significant classes of behaviors, 1) isotropic large deformation linear responses [1], 2) temperature-controlled uniaxial non-linear responses [2]. In the first research topic, we show that linear elasticity models are insufficient due to geometric nonlinearities. To address this, we have developed an algorithm for accelerating homogenization and the design of microstructures that exhibit nonlinear elasticity. The method constructs an accurate representation of a microstructure's deformation over a range of macroscopic strains. This allows for efficient calculation of the material's effective properties at any strain. The design tool then optimizes these properties to match a target hyperelastic constitutive relationship, enabling the synthesis of a fabricable geometry. In the second research topic, we design architected materials that behave in target manners at target temperatures. This is achieved through a topology optimization based computational morphogenesis and multimaterial polymer 3D printing. Different polymers with distinct glass transition temperatures are used to create microstructures that can undergo large deformations with temperature-controlled nonlinear mechanical responses. These architected materials, with their complex geometries, demonstrate variable force-displacement relations and deformation patterns as the temperature changes.

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Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMIC FRACTURE SIMULATION OF QUASI-BRITTLE MATERIALS USING A GENERALIZED MICROPOLAR PERIDYNAMIC MODEL

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ABSTRACT

A generalized micropolar micropolar peridynamic model is proposed to simulate the dynamic fracture behaviors of quasi-brittle materials. The governing equations of bonds connecting particles are reformulated from the definition of bond deformation rates, leading to a rate-based expression of mechanical behavior of solid particles. The peridynamic parameters are derived as time-dependent functions with the consistence of the strain energy obtained from the proposed peridynamic model and the continuum mechanics. The damage evolution functions are introduced in the model to capture the loading-rate dependence of rock. Moreover, a new failure criterion is proposed to describe the dynamic fracture progress of rock materials. The proposed model is verified by comparing its results with those from experimental observations. Numerical examples demonstrate that the dynamic fracture behaviors of rock materials under loads with different loading rates are well captured by the proposed model.

A CLOSED-FORM CRITERION TO IDENTIFY HIGH-MOBILITY FLOWSLIDES

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ABSTRACT

Slope failures induced by fluid injection, like rainfall and groundwater rising, have been a severe concern not only to local environment, but also to the populations residing nearby. This work proposes a unified modeling framework to simulate pre- and post-failure motion in infinite slopes. This sliding-consolidation model enables a comprehensive examination of the factors that dominate the triggering mechanisms of landslides and control whether the landslide motion, once triggered, autonomously comes to rest (self-regulating behavior with low mobility) or continues to propagate (self-feeding behavior with high mobility). Rely on such a framework, a closed-form criterion to assess the risk of flowslide runout is derived for the loose frictional soil considering a perfectly plastic constitutive law. Such a solution is used to build charts to identify the critical ranges of soil properties and triggering factors that differentiate between high-mobility and low-mobility flowslides. Most importantly, it is shown that the fate of flowslide motions is predicted by a critical ratio expressed in terms of excess pore pressure and flow velocity, here defined factor of mobility, FM, with values above 1 indicating a self-feeding runout.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OXIDATION LEVELS AND CONFIGURATIONS IN GRAPHENE OXIDE INFLUENCE THE MECHANICAL AND VISCOELASTIC PROPERTIES OF PMMA NANOCOMPOSITES

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ABSTRACT

Recent advancements in polymer nanocomposites have highlighted their superior mechanical properties compared to pristine polymers. Graphene oxide (GO), a derivative of graphene, is a promising candidate for enhancing the mechanical properties of polymers, owing to its high strength and toughness and robust adhesion with polymers. Despite extensive investigations on the mechanical properties of GO-polymer nanocomposites, the effects of the oxidation levels and configurations of GO sheets on the viscoelastic properties of polymer nanocomposites remain poorly understood. In this study, we explore the impact of varying oxidation levels in graphene oxide (GO) on the mechanical properties of GO-reinforced poly(methyl methacrylate) (PMMA) nanocomposites using coarse-grained (CG) molecular dynamics (MD) simulation. We emphasize two distinct configurations of the nanocomposites with either separated or stacked GO sheets. Our findings reveal that changes in the oxidation level of GO have a minimal effect on the tensile modulus for both configurations as well as on the shear modulus for the separated configuration. However, we find that under shear deformation, the stacked GO cases show a strong dependence on the potential sliding events between GO sheets that arise from weaker GO inter-sheet interactions and stronger GO-PMMA adhesions. Specifically, the shear modulus notably increases with increasing oxidation levels for the stacked cases. This enhancement is attributed to the stronger local confinement of PMMA, which mitigates the instability of the stacked GO sheets. Furthermore, the stacked cases with higher oxidized GO exhibit higher storage modulus, slightly lower loss modulus, and significantly lower tangent loss during small amplitude oscillatory shear (SAOS) tests, owing to the enhanced local confinement of PMMA which allows the shorter interlayer sliding of the GO sheets. By comparing their counterparts with separated cases, it is conclusive that the interlayer sliding magnitude is the dominant factor in the viscoelasticity behaviors of such nanocomposite, and a positive correlation is found between the tangent loss and sliding magnitude of GO sheets. This study demonstrates oxidation levels and configurations of GO sheets can significantly influence the mechanical and viscoelastic properties of GO-polymer nanocomposites.

GRAPH OSCILLATORS: A PHYSICS-GUIDED GRAPH MODELING OF A MASS-SPRING-DAMPER SYSTEM FOR TRAJECTORY PREDICTION AND DAMAGE LOCALIZATION

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ABSTRACT

Recognizing that a multiple-degree-of-freedom oscillatory system can be viewed as a group of connected nodes, this paper presents a novel computational framework that learns coupled oscillations by a graph, a mathematical structure describing pairwise connections between objects. Further reinforced by an incomplete equation of motion, data-driven neural networks and an anti-symmetric coupling constraint, we can capture statistical patterns of unknown coupling mechanisms (or nodal interactions in the language of graph models) using limited data. The proposed physics-guided data-driven method demonstrates a strong predictive capability even for unseen control inputs, outperforming three widely studied black-box and grey-box counterparts in synthetic and experimental case studies. In addition to its predictive capability, the distributed parameterization of nodal interactions allows us to investigate local anomalies/damages by monitoring updates after transfer learning. While the limits of the current method are discussed, it displays the potential of a generalizable and interpretable meta-model for simulating trajectories as well as identifying the system's status.

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISASTER SCENE MODELING: FROM PHOTOGRAMMETRIC TO GENERATIVE AI TECHNIQUES

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ABSTRACT

Images depicting scenes of disaster events, including structural and geotechnical damage, hazard evidence, and other characteristic impacts to other objects (e.g., trees and landscapes), have long been used by researchers and first responders in post-disaster reconnaissance. Recently, digital technologies such as mobile smartphones, LiDAR, portable 3D imaging, augmented reality devices, unmanned aerial vehicles, and social networks as sensors have vastly expanded imaging modalities for recording and curating disaster scenes. To manage the data volume and enhance understanding, traditional photogrammetry methods, particularly structure-from-motion (SfM), are commonly employed for producing rendered 3D models and mapping products like contour plots and computer vision-based damage assessment. However, this multi-phased process involves computationally intensive and varied nonlinear optimizations, including camera calibration, pose estimation, bundle adjustment, point-cloud extraction, and meshed-model generation. Machine learning technologies are transforming this photogrammetric field. One notable example is the Neural Radiance Fields (NeRF) technique, which employs AI to learn a scene's geometry, camera poses, and object reflectance, rendering photorealistic 3D scenes. The most advanced technique to date, 3D Gaussian Splatting (3D-GS), overcomes critical NeRF limitations, such as pose estimation dependency, extensive training and rendering time, and sensitivity to large motion changes. Crucially for practical implementation, a 3D-GS-based approach paves the way for an end-to-end generative pipeline, processing input (like video frames) to output (such as reconstructed 3D scenes or novel view synthesis).

In our presentation, we will showcase our 3D Gaussian Splatting-based implementation, capable of rapidly generating 3D disaster scenes from diverse sources such as UAV-based aerial images, stereo camera-based, LiDAR-based, and social network-based inputs. With uncompromised 3D resolution in the resulting meshed models, we will also demonstrate engineering-significant steps in achieving damage and debris quantification, essential for objective resilience-based decision-making and disaster recovery.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ARTIFICIAL INTELLIGENCE AND AERIAL PHOTOGRAMMETRY FOR POST-HURRICANE DEBRIS DETECTION AND ANALYSIS

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ABSTRACT

This study aims to improve the assessment of post-hurricane damage and debris analysis. Rapid and reliable post-hurricane impact assessment is essential to response and recovery since unreliable assessments can hinder search-and-rescue (SAR) operations and resource distribution. Recent computing advancements have shown the potential of affordable unmanned aerial vehicles (UAVs), artificial intelligence (AI), and computer vision technologies in collecting data and assisting with post-hurricane reconnaissance in the built environment. However, the utilization of AI and UAV photogrammetry for damage detection and analysis still remains unexplored. To this end, we develop a framework that leverages rapid reality capture through aerial drone imagery and photogrammetry. The framework begins with the deployment of UAVs to obtain bird's-eye perspectives of disaster-affected regions, facilitating efficient reconnaissance. Following this, a vision-based AI model is trained to autonomously detect severely affected areas and pinpoint debris locations using aerial data as input. The 2D imagery acquired from UAVs is subsequently converted into 3D point clouds, generating a three-dimensional representation of the impacted region's infrastructures and wind-induced debris. The preliminary results showed that the trained region-based neural network can automatically detect wind-induced debris in drone imagery with approximately 80% average precision (AP). Our framework was validated in a testbed within Southeast Texas. We investigated the optimal density of 2D aerial imagery required to generate sufficiently accurate 3D models for comprehensive disaster impact analysis. The precision and accuracy of these point clouds hold particular significance in research areas related to time-sensitive disaster response and drone navigation. Our results indicate that, in the case of aerial imagery for infrastructure systems in the built environment, a minimum of 60% overlap is recommended for damage assessment and debris analysis. In contrast, for flat green areas, a minimum of 50% overlap is adequate. Overall, for disaster response applications, this study reveals that an overlap ratio between 60% and 70% is optimal for achieving a balance between time efficiency and data quality in aerial data collection.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SEMI-RESOLVED ALE-VMS-DEM FRAMEWORK FOR PARTICLE-FLOW INTERACTION

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ABSTRACT

Flow-particle interaction is a critical aspect in various engineering applications, including oil-gas transmission and additive manufacturing. Despite significant progress has been made, accurate and efficient method for flow-particle interaction still remain a challenge. This study introduces a general semi-resolved ALE-VMS-DEM framework for efficient and accurate flow-particle interaction simulations. We couple fluid dynamics and particle dynamics via a momentum exchange approach. In this framework, we develop a set of algorithms to handle particle-particle and particle-wall collisions within a Finite Element Method (FEM). We validate the proposed framework by simulating a single-particle sedimentation process and a multi-particle solid-liquid fluidization process. Good accuracy has been achieved. To further demonstrate the effectiveness of this proposed framework, we apply it to investigate the solid-liquid mixing in a stirred tank equipped with a blade turbine, showcasing its potential for large-scale practical engineering problems.

Advances in bridge health monitoring: Data-driven and machine learning methods, indirect monitoring, crowdsourced mobile sensing
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DIFFERENTIABLE MATERIAL POINT METHOD FOR INVERSE ESTIMATION IN SHM OF RAILWAY BRIDGES

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ABSTRACT

In the field of structural health monitoring (SHM), the application of inverse methods (i.e., parameter estimation) to inform data interpretation (e.g., damage detection) can be challenging, particularly when geometric and material properties have large uncertainties and when long-term fixed sensor networks provide sparse measurement data. Uncertain or unknown loading conditions can further complicate the problem. We developed a new Differential Material Point Method (DiffMPM) simulator to address this challenge of estimating structural and loading parameters given spatially separated dynamic SHM measurements.

The MPM model is initially set up with approximations of element parameters (such as Young's moduli and Poisson ratios) and loading conditions. Subsequently, the loss is calculated as the mean squared error between the predicted deflection of the beam and the actual structure measurement. Automatic differentiation is then employed to determine the gradients of this loss function concerning both element and loading parameters. This process involves iteratively refining the parameters through a pseudo-Newtonian method until a convergence threshold is reached. We employ variable learning rates to update the material parameters and loading conditions corresponding to the magnitude of their gradients.

Various 2D simulations will be presented to demonstrate the DiffMPM parameter estimation framework and its efficacy in assessing structural integrity and identifying areas of concern. A more detailed case study structure, a masonry rail bridge that has been monitored for several years, will also be presented to demonstrate the application of the DiffMPM framework to real-world situations with large uncertainty.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CRYSTAL PLASTICITY MODELING AND ANALYSIS FOR THE TRANSITION FROM INTERGRANULAR TO TRANSGRANULAR FAILURE IN NICKEL-BASED ALLOY AT ELEVATED TEMPERATURE

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ABSTRACT

The precipitation-strengthened Nickel-based alloy Inconel 740H (IN740H) exhibits increased ductility at higher applied strain rates during quasi-static tensile tests at an elevated temperature of 760C. This is opposite to the same class of precipitation-strengthened alloy such as H282 whose failure strain decreases at higher strain rate. The examination of IN740H fracture surfaces in this context reveals a noteworthy transition of underlying fracture mechanisms from transgranular to intergranular fracture as the applied strain rate decreases from 1x10^-3/s to 0.83x10^-4/s. To thoroughly understand and predict the mechanical response of IN740H under these conditions, this study develops a comprehensive crystal plasticity finite element (CPFE) model which considers three deformation mechanisms that are relevant to the material behavior at the corresponding temperature range, including dislocation slips, climb and grain boundary sliding-induced creep deformation. Correspondingly, the explicit grain boundary interface are incorporated into the model using cohesive elements. The model is calibrated using data from both tensile tests at different strain rates and creep tests across a broad stress range at 750C, enabling the accurate determination of model parameters for each mechanism. Simulation results well captured the experimental observations of different failure modes. At higher strain rates, the model shows a dominance of dislocation slip leading to heterogeneous plastic deformation and formation of transgranular shear bands causing the failure, while at lower strain rates, an increases activity of grain boundary sliding causes grain boundary crack and intergranular failure. The model and experiments cross-validated our hypothesis and will be used to further predict and analyze the more complex material response.

CRYSTAL PLASTICITY AND SURROGATE MODELING OF DEFORMATION AND MARTENSITE TRANSFORMATION OF HIGH-STRENGTH QUENCHING AND PARTITIONING STEELS

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ABSTRACT

Quenching and partitioning (Q&P) steels have gained prominence as promising candidate material in fabricating safety-critical components in automotive and aeroscape industries as it exhibits superior mechanical properties and good cold-formability. Recent research have shown the strength and ductility of cold-formed sample is sensitive to the volume fraction of retained austenite. The martensite transformation kinetics is sensitive to the local strain path and initial microstructure, which potentially lead to different spatial variation of retained austenite volume fraction in a part and enables controlling local tailored properties. In this presentation, a full field crystal plasticity finite element (CPFE) model is developed to capture the stress-assisted transformation kinetics of Q&P steels inside the heterogeneously deformed microstructure. The model integrates the detailed explicit microstructure, acquired from characterization experiments, into a high-resolution finite element mesh. It distinctly models the deformation and interaction between the various phases and the effect on the transformation of retained austenite. The model is validated with high energy X-ray diffraction (HEXRD) data, and shows excellent capability in predicting the asymmetric stress-strain behavior under uniaxial tension and compression, as well as the martensite transformation kinetics. Based on the CPFE model generated data under various strain paths, a surrogate model is further developed and validated for part level simulation and predicts the local transformation and resulted properties, providing a tool to facilitate the industry advancement of cold-forming technology for Q&P steels.

STRESS ANALYSIS OF SOLIDS VIA A MESHLESS METHOD USING ADAPTIVE WEIGHTED POLYNOMIALLY AUGMENTED RADIAL BASIS INTERPOLANTS

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ABSTRACT

Various solid mechanics problems have been studied using meshless methods. Originally, these methods have most commonly used moving least square (MLS) approximations, where more recently radial basis function (RBF) interpolation with polynomial reproduction and reproducing kernel approximations have been used. Particularly for the case of global RBF interpolations (with compact support), while such interpolation improves stability, accuracy is often low and convergence can often been slow, while both accuracy and convergence are controlled by polynomial augmentation. On the other hand, polynomial interpolation (as opposed to the MLS approximations) often results in singularities or ill-conditioning, which makes it unattractive and practically impossible to implement over arbitrary grids. This study proposes a local point interpolation method for the displacement field that utilizes adaptive weighted polynomially augmented (PA) RBF interpolants. This concept lies on the realization that polynomial interpolation, which drives convergence and accuracy, should control in the vicinity of the reference point (usually a quadrature point), whereas the RBF interpolation, which controls overall stability may be more dominant away from the reference point. To achieve this objective, the problem of polynomial augmentation of RBFs is recast through a weighted minimization framework that promotes short-range polynomial dominance over the support of each reference point. Furthermore, the size of the support (i.e. number of interpolated nodes) of each reference point is selected through an iterative adaptive scheme that ensures that error resulting from potential ill-conditioning remains below a target error tolerance. Using these adaptive weighted PA-RBF interpolants, the weak form of equilibrium is adopted to derive a discretized solution for the solid mechanics problem. Because the resulting shape functions have the Kronecker delta property, application of essential BCs is straightforward (similar to FEM). An intensive numerical study has been conducted to assess the accuracy and convergence properties of the resulting meshless method for various nodal distributions through various examples on 2D domains. Analyses are performed for both elastic and plastic material constitute relations.

Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYBRID DECISION MAKING FRAMEWORK FOR MOORING-LINE FAILURES OF FLOATING OFFSHORE WIND TURBINES

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[1]*New Mexico State University*

ABSTRACT

This study introduces an advanced maintenance framework that incorporates data-driven structural monitoring, specifically designed for the mooring line of Floating Offshore Wind Turbines (FOWTs). FOWTs pose challenges in terms of cost-effectiveness, with a major concern being the high estimated operation and maintenance costs, exacerbated by the distance of the sites from land. Offshore industries employ various strategies that need significant adaptation for the application of FOWTs. The proposed approach integrates Artificial Intelligence (AI) with a probability-based maintenance practice. The proposed method was tested with a semi-submersible NREL 5MW OC4-DeepCWind FOWT. Deep learning algorithms, including gated recurrent unit (GRU) and long short-term memory (LSTM) networks, were implemented and integrated with a Bayesian-based probabilistic prediction method. Sensing data, encompassing displacement information from GPS sensors, accelerometers, and vibration-based velocity sensors, was utilized. It is intended to minimize the number of sensors while maintaining the reliability of the sensor data. Accidental failures of the sensors are considered in the framework. The goal is to enhance the prediction of FOWT failures and improve the cost-efficiency of maintenance plans through the proposed method, which is informed by sensing data.

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MOORING FATIGUE RELIABILITY OF FLOATING OFFSHORE WIND TURBINE

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ABSTRACT

Offshore structures are known to fail predominantly due to fatigue due to their dynamic environments consistently agitated by wave and wind loads. Fatigue is a major causes that significantly shorten the lifespan of offshore structures. Although the industrial codes provide simplified methods of fatigue failures, due to the high uncertainties of the offshore environments, its prediction has been challenging. The purpose of this research is to develop a probabilistic model for the mooring fatigue failures of Floating Offshore Wind Turbines (FOWT)'s and quantify the uncertainties in the prediction of fatigue failure, provide the life-cycle reliability of FOWT's mooring. To demonstrate the method and model, the 5MW NREL OC4-DeepCWind, a semi-submersible benchmark FOWT, is employed to predict the life-cycle reliability of its mooring lines. Two types of mooring lines in FOWTs are analyzed. The first involves a traditional steel chain mooring, for which fatigue curves are established but used without accounting for uncertainties. Nylon mooring lines are analyzed, which emerges as a feasible alternative to address the current challenge of high costs. However, the material involves significant fatigue uncertainty compared to traditional steel materials. The resulting uncertainties in fatigue failures will be compared in terms of their reliabilities in the context of the safety factors to be considered in practice. This research contributes to the advancement of wind energy and other offshore infrastructures.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRAGILITY ESTIMATION FRAMEWORK FOR PERFORMANCE-BASED STRUCTURAL DESIGN OF FLOATING OFFSHORE WIND TURBINES

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ABSTRACT

This study proposes a computational and mathematical framework aimed at assessing the reliability of structural components within Floating Offshore Wind Turbines (FOWTs) that reflects various sources of uncertainty, including parameter and modeling uncertainties, and the uncertainties coupled between structural analyses, hydrodynamics of the floating structures, and the servo-aerodynamics of wind turbines. The parameter uncertainties include those involved in environmental loads, material properties, and structural geometries. The paper outlines structural failure modes, including bending, shear, and drift failures in wind turbine tower structures, defined through limit state functions. Fragility surfaces are developed for a chosen benchmark FOWT under both operational and parking conditions. The study analyzes and presents the impact of parameter uncertainties, such as wind speed variations, on structural reliability. Fragilities are also estimated for 50-year and 100-year environmental conditions in selected U.S. coastal regions, including Central California, West Central Gulf of Mexico, North Atlantic, and South Atlantic.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEQUENTIAL STRESS AND FABRIC ANALYSIS BY A NON-LINEAR VARIATIONAL AUTO-ENCODER

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ABSTRACT

In this study, we introduce a novel deep-learning framework employing a NonLinear Variational Autoencoder (NLVAE) to analyze the mechanical behavior of two-dimensional composites with embedded cracks. The novelty of our approach is the implementation of a non-linear latent variable prior based on the skew-normal distribution. The latent distribution thus comprises skewness and tailness. This enhancement overcomes the standard axis-aligned Gaussian assumption in classic Variational Auto-Encoders (VAEs), thereby expanding the exploration of the latent space. The data set used to train, validate and test the deep learning algorithm is a collection of sequences of stress fields obtained numerically, by simulating the response of a 2D solid with embedded cracks to uniaxial tension, uniaxial compression and pure shear tests. The solid is modeled with the Finite Element Method (FEM).

The performance of the non linear VAE is assessed from measures of reconstruction error, linear and non-linear latent feature correlations, and stress concentration prediction accuracy. The latter is calculated through two successive applications of a Gaussian Mixture Model (GMM) to both the input $\mathbf{x}$ and output $\hat{\mathbf{x}}$ of the VAE. Our findings demonstrate that the NLVAE captures stress concentrations, especially when enhanced disentanglement is emphasized during training. To assess the relevance of the latent variables to identify important microstructure changes during loading, we define the 43 fabrics from the undirected graphs formed by activated cohesive zone elements during loading. Distances between sequences of crack graph descriptors and stress latent features are measured by Dynamic Time Warping (DTW) to analyze the temporal sequences, and Earth Mover's Distance (EMD) calculations to track the dynamic shifts in tensors across the loading steps. Our results show that the NLVAE can capture fabric transitions and highlight the statistical descriptors of the crack pattern that best explain the stress field.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IN-LINE QUALITY CONTROL FOR ADDITIVELY CONSTRUCTED CONCRETE STRUCTURES USING 3D-LASER SCANNING

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ABSTRACT

With the evolution of additive construction (concrete 3D printing), the construction industry has been exploring this revolutionary technology to optimize structural and non-structural components to achieve more efficient, cost-effective, and durable elements [1]. In this sense, regulations for inspecting 3D-printed concrete structures and elements must be established to better control the quality of printed structures and elements [2]. Particularly for concrete 3D printed elements, ongoing research is being conducted by our team at Rowan University to capture the geometrical changes of each printed layer as printing progresses. To achieve this, the team is evaluating the use of remote sensors such as Light Detection and Ranging (LiDAR) to capture the geometry and characterize the printed layers. This research incorporates the use of stationary LiDAR, a FARO Focus 150, and mobile LiDAR, an Ouster REV7 OS0-128, to take advantage of the benefits of both sensors and reduce their shortcomings, by scanning the 3D printed elements throughout the printing process to monitor the behavior of the printed layers. Other researchers have used Computer Vision to monitor concrete additive construction [3], this research evaluates the capabilities of both scanners to capture changes in geometry, such as width, thickness, and length, that can lead to cracking, as well as local and global defects. Moreover, after the elements were subjected to load testing, additional scans were performed to characterize the damaged surfaces and investigate potential correlations between their geometry (e.g., damage location within the element, crack angle, surface roughness, among others) and the performance responses. This research presents a comparison between remote sensors in terms of percent error for capturing width variation, length variation, thickness variation, and crack detection.

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MAXIMUM ENTROPY-BASED MODELING OF COMMUNITY-LEVEL HAZARD RESPONSES FOR CIVIL INFRASTRUCTURES

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ABSTRACT

Perturbed by natural hazards, community-level infrastructure networks operate like many-body systems, with behaviors emerging from coupling individual component dynamics with group correlations and interactions. It follows that we can borrow methods from statistical physics to study the response of infrastructure systems to natural disasters. This study aims to construct a joint probability distribution model to describe the post-hazard state of infrastructure networks and propose an efficient surrogate model of the joint distribution for large-scale systems. Specifically, we present maximum entropy modeling of the regional impact of natural hazards on civil infrastructures. Provided with the current state of knowledge, the principle of maximum entropy (Jaynes 1957) yields the ``most unbiased`` joint distribution model for the performances of infrastructures. In the general form, the model can handle multivariate performance states and higher-order correlations. In a particular yet typical scenario of binary performance state variables with knowledge of their mean and pairwise correlation, the joint distribution reduces to the Ising model in statistical physics. In this context, we propose using a dichotomized Gaussian model as an efficient surrogate for the maximum entropy model, facilitating the application to large systems. Using the proposed method, we investigate the seismic collective behavior of a large-scale road network (with 8,694 nodes and 26,964 links) in San Francisco, showcasing the non-trivial collective behaviors of infrastructure systems.

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Repair and assessment of deteriorating critical infrastructure
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENTROPY BASED LIFE CYCLE FRAMEWORK FOR INSPECTION AND MANAGEMENT OF MARINE STRUCTURES

Akshat Chulahwat[1] and Hussam Mahmoud[1]*

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ABSTRACT

Steel structures are particularly vulnerable to fatigue damage as the experienced cyclic loading can result in multiple cracks at fatigue-prone locations. Fatigue cracks are not considered immediate priority but over the life of a structures they can prove to have catastrophic consequences if left unchecked. Accordingly, careful maintenance and repair actions are required to maintain the integrity of the structure while limiting the associated cost, particularly for marine structures since their deteriorate at a fast rate. Significant research has been conducted on developing life-cycle cost optimization frameworks for inspection and management of marine structures based non-linear optimization algorithms. While the accuracy of these algorithms is significant for limited number of optimization variables (crack locations), a reduction in accuracy is observed as the optimization variables increase. In this prestation, we will discuss a newly developed probabilistic life-cycle cost framework that improves on existing approaches by utilizing the concept of Information Entropy to reduce the number of optimization variables required. A life-cycle cost analysis is conducted on a ship structure assuming simultaneous crack generation at multiple locations. The minimum life-cycle cost calculated based on the proposed life-cycle framework and the selected non-linear optimization-based framework are compared for three cases of target lives considered. The proposed framework demonstrated both lower cost and significantly lower convergence time in all cases. The Entropy based life cycle framework can be particularly beneficial for large structures prone to multiple fatigue cracks.

VALIDATION CASE STUDIES FOR THE AGNI-NAR WILDFIRE COMMUNITY VULNERABILITY AND DAMAGE MODEL

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ABSTRACT

In recent years, the impact of wildfire events has been devastating on the natural and built environment. Given the changes brought on by climate change, the frequency and intensity of wildfire events is expected to further increase. Combined with the increasing population in the wildland-urban interface (WUI) region, methodologies are required to better understand the impact of wildfire events on the built environment. Unlike other natural hazards, like earthquakes, floods or hurricanes, no universal framework exists for wildfires capable of predicting the damage on the built environment due to wildfire events. Recently, a model based on concepts of graph theory was developed to represent the interactions between wildfires and the built environment as a network, such that nodes represent the ignitable fuels and edges represent the probability of ignition between the fuels. To evaluate the impact on the built environment a relative vulnerability metric is developed based on the concept of graph centrality measures to determine the relative likelihood of ignition, which is used to obtain the damage state for individual fuel nodes. To test the efficacy of this metric, the graph framework was tested on four destructive wildfire events in the US – Camp fire (California), Glass fire (California), Marshall fire (Colorado) and Lahaina fire (Hawaii). The actual damage state observed of individual structures in each case were compared to the calculated damage states based on the graph framework to determine the prediction accuracy. The graph framework demonstrated a prediction accuracy of 86% for the Camp fire, 64% for the Glass fire, 74% for the Marshall fire and 72% for the Lahaina fire. With the capability of predicting damage, the graph network can be utilized to develop a holistic impact assessment framework for wildfires.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONDITIONS FOR STEADY CREEP, ASESMIC TRANSIENTS, AND SEISMIC SLIP IN A SINGLE-ASPERITY STRIKE-SLIP FAULT

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ABSTRACT

Knowing a-priori whether a fault is more likely to accommodate steady creep, aseismic transients or seismic slip is of great importance for many sub-surface engineering operations, such as geological carbon sequestration or geothermal energy extraction from tight fractured reservoirs. For instance, the presence of a fault in a caprock may jeopardize its sealing integrity and hence promote CO2 fluid migration if aseismic transients or seismic slip take place on such a fault.

In this contribution, we provide a deterministic framework that predicts whether slow (aseismic) or fast (seismic) slip occurs on a fault whose strength is governed by rate-and-state friction and loaded by steady creep at its extremities. We use linear stability analysis to determine whether slip rate on a rate-weakening asperity on the fault, embedded within an otherwise stable, rate-strengthening surface, is expected to diverge or not from a reference stable configuration upon small perturbations. This allows to define semi-analytically the (minimum) critical asperity size that could eventually support a dynamic instability as a function of governing dimensionless parameters.

For a given rate-strengthening condition surrounding the asperity, we show that its critical size decreases non-linearly with decreasing values of a/b (<1) characterizing the asperity, with b and a being the phenomenological parameters of rate-and-state friction. When the critical asperity size is much smaller compared to the total fault length, we show that its value agrees well with the calculated critical size of a single asperity within an infinitely long fault, whose value is shown to increase logarithmically the less pronounced rate-strengthening condition is around the asperity.

When an asperity is larger than its critical value obtained from linear stability analysis, we show another critical dimension plays a role in discriminating whether or not the diverging slip rate reaches seismic velocities, for which inertia is mobilized and waves radiated. This critical dimension accounts for elasto-frictional non-linearity. For a given set of problem parameters, it is uniquely determined by solving a free boundary problem of a slip-weakening crack model in equilibrium with external forces [1].

By determining semi-analytically these critical dimensions, we can construct a phase diagram that allows to precisely predict the possible slip dynamics on a single-asperity strike-slip fault. Full elasto-dynamic simulations using a newly developed Spectral Boundary Integral Equation Method-based code confirm and support our theoretical predictions.

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Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATION OF A TRANSFER LEARNING APPROACH TO MULTI-FIDELITY WIND LOADING PREDICTIONS

Mattia Ciarlatani[1] and Catherine Gorlé[1]*

[1]Stanford University

ABSTRACT

This study investigates the application of transfer learning within a multi-fidelity (MF) framework based on large-eddy simulations (LESs) to predict wind loading on high-rise buildings. We combine a large number of coarse LESs, which represent the low-fidelity (LF) data, with a few fine LESs, which represent the high-fidelity (HF) data, to provide accurate wind loading predictions for the full wind rose. This work will build on a previously developed multi-fidelity framework that uses a neural network as a surrogate model to reconstruct the discrepancy between the low- and high-fidelity model responses for a high-rise building with a rectangular floor plan.

First, we perform low- and high-fidelity LES simulations of three high-rise buildings with rectangular, L-shaped, and square floor plans for different wind directions with a 10° resolution. Second, we pre-train a neural network on one of the three high-rise building models by leveraging LF and HF data for every available wind direction. Third, some layers of the neural network are frozen, and the remaining layers are trained using data from each of the two remaining building shapes. To retrain the neural network, we will use both LF and HF data at 5 wind directions, and to test the model we predict the LF model discrepancy at 5 wind directions withheld from the training set of each shape. Finally, the predictions from the transferred neural networks are compared with the predictions of a neural network exclusively trained on a specific shape. This will offer insight into the feasibility of transfer learning within the context of multi-fidelity wind loading predictions.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCING AERO-STRUCTURAL OPTIMIZATION METHODS FOR LONG-SPAN BRIDGES: FROM SYNOPTIC TO NON-SYNOPTIC WIND DESIGN SCENARIOS

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ABSTRACT

The governing design load of most long-span bridges is the action of wind. The deck cross-section is fundamental to controlling the global response of the bridge as it impacts its structural and aeroelastic responses by contributing to both the mechanical and aeroelastic properties. This can only be properly managed by adopting holistic design frameworks involving multiple design variables that define the deck configuration, cable supporting system, and tower design, and numerous design constraints that enable limiting the structural responses, such as stress levels and displacements at the global and member levels, and all relevant aeroelastic responses, such as flutter and aerostatic instabilities, buffeting, and VIV (Cid Montoya et al. 2022). The capacity of wind-resistant design methods relies on accurate wind modeling to properly quantify the wind-induced responses during the design process. Bridge design in synoptic wind scenarios, which entail negligible variations in the mean wind velocity and angle of attack, can be commonly carried out by adopting frequency-domain methods or linear time-domain approaches. Furthermore, the quasi-steady theory can estimate the fluid-structure interaction parameters with acceptable accuracy when designing streamlined single-box decks at high reduced velocities. However, as the deck cross-sections considered as design candidates are no longer streamlined, which can include bluff single-box decks, traditional truss decks, or modern multi-box decks, and non-synoptic winds are considered in the list of design scenarios, new modeling and design approaches are needed. This involves adopting nonlinear time-domain methods for assessing the wind-induced responses and extracting the fluid-structure interaction parameters as a function of the deck shape, reduced velocity, and angle of attack to capture all eventual aerodynamic nonlinearities (Kareem and Wu, 2013). The optimization strategy must be reformulated, and the emulation techniques must be efficiently used to produce design frameworks with acceptable computational burden. This study discusses the required wind modeling approaches to achieve the desired accuracy in each design scenario and the kinds of simulations needed to optimize bridge designs. Several illustrative examples will be presented and discussed, focusing on the efficient formulation of the aero-structural optimization frameworks.

Keywords: aero-structural optimization, long-span bridges, deck shape

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Probabilistic learning, stochastic optimization, and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SPARSE LEARNING OF A SEMI-EMPIRICAL AERODYNAMIC MODEL USING BAYESIAN INFERENCE FOR NONLINEAR AEROELASTIC SYSTEMS

David Clarabut[1], Brandon Robinson[1], Rimple Sandhu[2], Mohammad Khalil[3], Chris Pettit[4], Dominique Poirel[5] and Abhijit Sarkar[1]*

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[2]National Renewable Energy Laboratory
[3]Sandia National Laboratories, Livermore
[4]United States Naval Academy
[5]Royal Military College of Canada

ABSTRACT

Previously, an aeroelastic model was developed to model the low-amplitude limit cycle oscillations (LCO) of a rigid airfoil undergoing rigid body base rotation in pitch [1]. This setup was inspired by a wind tunnel apparatus at the Royal Military College of Canada. The proposed semi-empirical unsteady aerodynamic model aims to model the LCO behaviour of the airfoil by coupling the structural dynamics model with an aerodynamic model that is expressed as a polynomial function of the pitch angle and pitch velocity. The semi-empirical model includes linear stiffness and damping terms along with Duffing- and Van der Pol-type nonlinear stiffness and damping terms, respectively. The polynomial model is parameterized by time-invariant coefficients that are estimated from data.

This work consists of extending the aerodynamic model for a single-degree-of-freedom airfoil in [1] to the case of systems having multiple degree-of-freedom. Two additional wind tunnel setups include the classical pitch-plunge airfoil, and a bending-pitch model. While the pitch-plunge model couples two rigid body modes, a rotation and a translation, the bending-pitch model couples the same rigid-body motion in pitch with the bending vibrations of a continuous system modelled as a cantilever. As this is the first foray into applying this semi-empirical aerodynamic model to such cases, the optimal combination of aerodynamic terms in pitch, plunge/bending, and the combination thereof is not known a priori. Hence, we leverage the nonlinear sparse Bayesian learning (NSBL) algorithm [2], to discover the optimal nonlinear aerodynamic model. This methodology was shown to provide an efficient mechanism for Bayesian model selection for nested models in [2], which specifically studied the case of an elastically mounted rigid pitching airfoil. The use of NSBL leverages a robust semi-analytical inference framework that enables the use of automatic relevance determination (ARD) priors for optimal prior selection even in the case of highly non-Gaussian systems. The resulting sparse model alleviates overfitting, revealing a data-optimal form of the aerodynamic model.

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Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INCREASING HIGH-FIDELITY MODELLING EFFICIENCY WITH AUTOMATION AND MACHINE LEARNING

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ABSTRACT

To have a fast response to an accidental release of poisonous gas, it has been an URGENT request to create a ‘real-time’ prediction computer model for an accurate estimation of near-source dispersion within several hundred-metre-distance urban areas. This has been an extremely challenging task for decades, and is because 1) an accurate prediction requires a resolution of about 1 metre within a 1km X 1km and 1km computational domain, creating a massive computational cost; 2) the local geometry is usually complex and is time consuming to convert it into a computational domain; 3) the external conditions, e.g. the weather conditions, have large uncertainties and may substantially cause significant errors in the prediction. To deal with the above challenges so far, one approach is to improve and to stretch the Gaussian type dispersion model towards predicting near-source dispersion, such as the CERC’s ADMS model. Another approach is to carry out precursor simulations over each grid (e.g. 1kmX1km blocks) of a city of interest, to parametrise the simulated wind velocities and turbulent quantities for each grid, therefor to setup a fast predictive model applicable for that city, such as the CT-Analyst model. Both these types of model have certain strengths and limitations.

The current study has two aims. The first is to reduce the time taken to conduct high-fidelity modelling of chemical plumes through the use of automation; the second is to reduce the number of simulations and maintain accuracy by using machine learning. In order to correctly model downstream dispersion, in particular near field dispersion, a good prediction of the flow field is critical. Large Eddy Simulation (LES) is used to resolve the energetic eddies generated within the urban boundary layer. This study makes use of Palm4U and the efficient synthetic inflow turbulence generation. We have run several tests for the City of London, Southampton City and Bristol City, to demonstrate that it is achievable to run simulations at “real time” with small grids and suitable computing power. To drastically reduce the time required an automation tool is developing. This includes the entire setup process, which includes downloading terrain and building data from internet, creating the mesh file, setting up boundary conditions and generating the required input files. Finally, through the use of machine learning, the study aims to reducing the uncertainty due to the lack of data or inaccurate data of upstream wind direction.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADAPTIVE SPACETIME WAVELET METHOD FOR THE SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS

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ABSTRACT

The size and complexity of the problems presented to the computational physics community is constantly growing. Efficient and accurate solutions of coupled systems of partial differential equations (PDEs) are needed to meet this growth. Moreover, the solutions to many of these problems contain features that evolve both in space and in time. The vast majority of existing methods use semi-discrete techniques to discretize PDEs first in space and then use a marching method to integrate in time. Many of these techniques encounter either a bottleneck in computational resources or an inability to accurately capture the features of the solution. In this work, we present a novel spacetime method using wavelets bases that offers a solution to these issues.

The proposed wavelet method can be described as a pseudo-spectral method that uses biorthogonal interpolating wavelets and second-generation boundary-modified wavelets to solve initial-boundary value problems. This method is based on Multiresolution Analysis (MRA) due to the ability to selectively focus resolution where warranted. We compute both spatial and temporal derivatives by applying wavelet derivative operators directly to the bases. Unlike many methods, we use wavelets and derivative approximations to discretize our problem not only in space, but simultaneously in time. As a result, we circumvent marching strategies that may introduce error or inefficiency, and find the solution over the entire spacetime domain in a single step for linear problems or using Newton's method for nonlinear.

We have demonstrated the capability of our solver using both linear and nonlinear examples. In the linear case, the problems take the form of a Sylvester Equation, for which we have implemented the restarted global GMRES/Arnoldi method. For linear problems, we are able to leverage wavelet synthesis to generate intelligent initial guesses. In the nonlinear case, we present multiple forms of the Burgers' Equation as well as Sod's shock tube problem using the Navier-Stokes equations. We present spacetime solutions on both a dense grid with high-order convergence as described by wavelet theory, as well as some preliminary solutions on an adaptive grid.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FAMILY OF FRAME ELEMENTS WITH DAMAGE EVOLUTION FOR STEEL STRUCTURES

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ABSTRACT

The failure analysis and probabilistic risk assessment of structures require the use of sophisticated numerical models for locating and quantifying the level of damage under a given excitation. The accuracy of these numerical models is crucial for evaluating a structure's performance in line with experimental observations. However, for large-scale simulations under multiple loading scenarios, e.g., several earthquake ground motions, it is of equal importance that these models are computationally robust and efficient.

This study aims to develop efficient analytical capabilities for simulating the inelastic response of steel frames under the strength and stiffness deterioration they experience when subjected to extreme events. To this end, a family of three-dimensional frame elements based on damage-plasticity is presented, with continuous degradation of strength and stiffness as a function of one or more damage indices. These elements are suitable for assessing the damage of multistory steel frames up to the point of incipient collapse. The damage evolution function accounts for low-cycle fatigue, different rates of damage accumulation in primary and follower deformation cycles, and the effect of damage accumulation in one loading direction on the behavior in the opposite direction.

The damage model operates as an independent wrapper of the effective force-deformation relation of the element, section, or material, returning the true forces or stress resultants and the true tangent stiffness of the force-deformation relation under damage. With this modular formulation, it is possible to generate a family of deteriorating frame elements based on resultant plasticity or distributed plasticity with varying degrees of accuracy and complexity. The response of the proposed frame elements is compared to available experimental data from the degrading hysteretic uniaxial and biaxial bending response of steel columns under constant and variable axial force. These comparisons lead to recommendations on a consistent set of damage parameter values for typical steel members.

This study's findings contribute to the development of efficient, robust, and accurate numerical models for the seismic risk assessment and failure analysis of steel frames subjected to extreme loading conditions.

UNDERSTANDING THE COUPLING EFFECT OF HIGH RAP AND WARM MIX ASPHALT FOR PRODUCING SUSTAINABLE ASPHALT PAVEMENTS

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ABSTRACT

Over the past few years, the construction of asphalt pavements has experienced significant growth, causing a shortage of essential pavement materials, including asphalt binder and mineral aggregates. From this perspective, recycling asphalt pavements has become a prevalent practice for pavement construction. However, the use of recycled asphalt pavement (RAP) is limited, typically ranging from 10-30%, due to the stiffening effect of aged binder in RAP material. In Oregon, the RAP content is restrained to 30% for a Level 3 asphalt mix design intended for moderate to high-traffic regions. In this study, an attempt has been made to explore the possibility of increasing the RAP content to 40% with the application of warm mix asphalt (WMA) technology. RAP mixtures at 30% and 40% RAP content were prepared with three different binder contents (5.5%, 6%, and 6.5%) using a PG64-22 binder, both with and without WMA. The attributions on the synergistic use of RAP and WMA were made based on laboratory performance tests such as the Hamburg Wheel Rut Test (HWTT) and the Indirect Tensile Cracking Test (IDT-CT). The rutting and cracking performance was assessed and subsequently compared using a 30% RAP mix as a control asphalt mixture, irrespective of the binder content. Test results were analysed using Fisher's least significant difference (LSD) and Tukey's honestly significant difference (HSD) post-hoc analysis to understand RAP and WMA's coupling behaviour on the rutting and cracking performance. Although the addition of WMA additive imparts softness to the asphalt binder, the results showed that the softening effect is counteracted by the inclusion of high RAP content (40% RAP) in the asphalt mixture. On the other hand, the use of high RAP content tends to increase the cracking potential, while the application of WMA technology leads to cracking behavior comparable to that of the control asphalt mixture. Findings revealed that the coupling effect of RAP and WMA ensures balance in terms of rutting and cracking potential. In addition, statistical analysis confirms that 40% RAP can be satisfactorily incorporated in asphalt mixtures with the use of WMA. Overall, the performance test results, along with post-hoc pairwise comparison analysis, suggest that WMA could be an effective solution to construct sustainable asphalt pavements with high RAP content in Oregon. This approach could reduce energy consumption, environmental impact, and economic concerns associated with pavement construction.

Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYSIS OF THE JOINT EFFECTS OF THERMAL STRESSES AND CORROSION ON INTEGRAL ABUTMENT BRIDGES

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ABSTRACT

The corrosion of reinforced concrete structures is highly dependent on local environmental exposure conditions. In coastal areas, this deterioration phenomenon can be particularly severe and can extend significantly in windy zones, since higher wind speeds allow for the deposition of a larger concentration of chlorides further inland. The greater the concentration of chlorides, the higher the steel corrosion rate. This connection between chloride deposition rate and steel corrosion rate has been proven in several studies [1]. Moreover, frequent temperature changes and exposure to extreme temperatures can induce wider cracks and micro-cracks in concrete structures, which can accelerate the diffusion of corrosive agents. In the case of integral abutment bridges [2], the combination of corrosion and extreme temperature variations may lead to the exceedance of some serviceability limit states and cascading negative effects on the proper operation of the road infrastructure, even before compromising structural safety.

Motivated by this evidence, the present study aims to verify the sensitivity of integral abutment bridges to the combined effect of thermal stresses and corrosion. The final goal is to quantify the risk of exceeding relevant serviceability limit states. To analyze the combined effects of thermal stresses and corrosion, an existing integral abutment bridge located in Shenzhen (Guangdong, China) is selected as a case study. In addition to thermal loads and corrosion effects, the bridge is also subject to traffic load.

The analysis considers three different limit states related to the maximum vertical displacement of the girders, the stresses in the lowest fiber of the concrete cross-section, and the stresses in the post-tensioned tendons. The preliminary results show that, in the long term, the combined effects of thermal loads, traffic load, and corrosion can lead to displacements that exceed the threshold set for the serviceability limit state by Chinese standards. Therefore, it is necessary to accurately estimate the probability of loss of functionality of the bridges to design actions that prevent such loss of functionality and the consequent impact on road infrastructure.

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Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING SHOCK ATTENUATION IN GRANULAR MATERIALS: THE ROLE OF PARTICLE SHAPE

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ABSTRACT

Protection against accidental loading, such as impact or blast, is of primary importance to the design and resilience of critical infrastructures systems in the energy, transportation and defense sectors. Shock absorbers are employed to dissipate energy, ensuring serviceability or structural integrity under extreme conditions. The design and deployment of shock absorbers entail complex challenges. Technologies based on polymers or epoxy are affordable and easy to manufacture but can have lengthy processes, e.g., curing, and the dimensions of the structures they can shield is limited. Foams are lightweight and have good energy dissipation properties but can be difficult to manufacture and characterize, and continuum modeling of cellular structures under extreme irreversible deformations is theoretically and computationally difficult.

Granular shock absorbers appear as a viable alternative to these traditional solutions thanks to their singular ability to dissipate and disperse energy. Granular materials also possess several practical advantages, namely: abundance, low cost, and ease of processing. The mechanical response of granular shock absorbers is characterized by the grain sizes, shapes, packing arrangement, and constitutive material. By varying these characteristics, the properties and performances of granular shock absorbers can be tailored and optimized.

This work performs a computational investigation of the effect of particle shapes on shock attenuation in granular materials. Discrete Element Modeling (DEM) of both spheres and non-convex cross-shaped grains is conducted. The grains are represented using the Bonded Particle Method (BPM), a robust methodology allowing simulation of grain deformation and breakage. Three-dimensional impact simulations highlight different speed of sound, and different pressure scaling of the shock front velocity for different shapes, generalizing results obtained on simpler systems. Redistribution of the energy from the shock wave into mechanisms unable to perform macroscopic work, e.g., grain rearrangement and ringing, demonstrates the dispersion and scattering capacity inherent to granular microstructures. These mechanisms are related to the deformation modes of the grain, which are controlled by their shape. Grain breakage enhances localization and is prevalent in non-convex grain shapes.
These results provide a novel conceptual and quantitative account of the effects of shape on shocks in granular materials and establish the capabilities to advance towards numerical prototyping and optimization of granular shock absorbers.

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DISSIPATION MECHANISMS OF CRACK-PARALLEL STRESS EFFECTS ON FRACTURE PROCESS ZONE IN CONCRETE

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ABSTRACT

A new experiment, named the gap test, has recently been developed to capture the influences of crack-parallel stresses on the fracture properties of quasi-brittle materials. Specifically for concrete, it has been shown that the fracture energy can either increase or decrease significantly according to the crack-parallel compression level. To simulate this phenomenon, computational models that assume the fracture process zone (FPZ) has a finite width and can characterize the FPZ of concrete tensorially are required. Although the finite element crack band model (CBM) with the physically realistic Microplane damage model M7 was quite successful in capturing the damage and fracture during the gap test, some questions require explanation, particularly the near doubling of the fracture energy at moderate crack parallel compression, which was underestimated by about 30%, and also the variation of the effective width of the FPZ and the evolution of energy dissipation within the FPZ. Presented here is an in-depth meso-mechanical investigation of energy dissipation mechanisms in the FPZ during the gap test of concrete, an archetypal quasi-brittle material. The Lattice Discrete Particle Model (LDPM) is used to simulate the quasi-brittle material at the length scale of major heterogeneities. The LDPM can accurately capture the frictional sliding, mixed-mode fracture, and FPZ development. The model parameters characterizing the given mix design are first calibrated by standard laboratory tests, namely the hydrostatic, unconfined compression, and four-point bending (4PB) tests, and then validated by the Brazilian split-cylinder tests and by gap tests of different sizes with and without crack-parallel stresses. The results show that crack-parallel stresses affect not only the length but also the width of the FPZ. It is found that the energy dissipation portion under crack-parallel compression is significantly more significant than it is under tension, which is caused by micro-scale frictional shear slips, as intuitively suggested in previous work. For significant crack-parallel stresses, the failure mode changes to inclined compression-shear bands of axial splitting microcracks.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARISON OF LATTICE DISCRETE PARTICLE MODELING (LDPM) IMPLEMENTATIONS: LESSONS LEARNED AND FUTURE WORK

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ABSTRACT

The Lattice Discrete Particle Model (LDPM) is a discrete mesoscale model of concrete that can accurately describe the macroscopic behavior of concrete during elastic, fracturing, softening, and hardening regimes. LDPM has been calibrated and validated extensively through the analysis of a large variety of experimental tests. LDPM can reproduce with great accuracy the response of concrete under uniaxial and multiaxial stress states in both compression and tension and under both quasi-static and dynamic loading conditions. The LDPM technology has been proven to supersede by far most of other available computational techniques for the simulation of concrete, especially for applications where the description of material internal structure and the link among different length scales is important.

The LDPM formulation is obtained by modeling the interaction among coarse meso-scale aggregate pieces as the interaction among polyhedral cells (each containing one aggregate particle) whose external surfaces are defined by sets of triangular facets. At each facet strain and stress vectors are used to formulate the constitutive law describing physical mechanisms such as tensile fracture, cohesion, friction, etc. In a similar discrete fashion, the effect of fiber reinforcement can also be taken into account.

The presentation will give an overview of recent implementations of LDPM in various computational platforms. LDPM was implemented in the following software packages: Abaqus/Explicit via user subroutine; Project Chrono, a physics-based modeling and simulation infrastructure based on a platform-independent open-source design; Cast3m a multi-physics software developed by CEA; Open Academic Solver, an open-source software developed at Brno University; JAX-LDPM, an open-source GPU-based software in active development by researchers from the Hong Kong University of Science and Technology; and FE-MultiPhys, developed at Virginia Tech. The different implementations will be compared by simulating typical failure tests for concrete, including, but not limited to, unconfined compression test, three-point bending test, and splitting tensile strength test.

Finally the presentation will provide a vision for future LDPM developments that will likely be implemented in these software packages.

INTERPRETING CHEMICALLY ASSISTED CRACK GROWTH IN CALCITE USING SURFACE FORCE-BASED FRACTURE THEORY

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ABSTRACT

Subcritical crack growth (SCG) plays a pivotal role in many geological processes, including delayed earth ruptures, weathering of surface rocks, and the relaxation of internal stresses within rock structures. Despite its significance, the mechanisms underpinning this chemically-driven cracking process—particularly the interactions at the nanoscale between crack walls and the transport of reactive species in the confined spaces near the crack tip—remain elusive. In this study, we apply the recently developed Surface-Force based Fracture Theory (SFFT) (Eskandari-Ghadi et al., 2022) for quantitatively analyzing the complex, multi-stage, non-linear SCG in calcite crystals influenced by aqueous solutions.

In SFFT, crack growth is a result of thermally activated debonding at the crack tip driven by the effective stress intensity factor contributed by both external loading and surface forces along the crack walls. Differing from conventional cohesive crack theories (Barenblatt, 1962), we consider the variation of surface force-separation relation with respect to the local species concentration, recognizing that surface-reactive species may not be evenly distributed along the crack. The species concentration profile is determined by Fickian diffusion and mole balance in the crack, thus is influenced by factors such as the relative velocity of the crack tip in comparison to its environment, the ambient concentration of reactive species, and the crack opening profile. The system of highly coupled equations is numerically solved via a partitioned implicit scheme for steady-state growth condition. The model is able to capture the chemistry-dependent crack threshold as well as the seamless transition between the three stages of SCG behaviors. We apply SFFT to investigate the impact of surface forces (such as DLVO and hydration forces) and ion transport on the SCG behavior of calcite crystals in NaCl solutions. After carefully constraining the model parameters, we found that hydration forces are much more influential than DLVO forces in determining the SCG curve of calcite at all NaCl concentrations. Additionally, ion transport in nanoconfined fluids emerges as a critical factor influencing SCG behavior at higher crack propagation speeds. These important fracturing mechanisms revealed by SFFT simulations can assist the future engineering of carbonate reservoirs for safe and effective extraction and storage of resources (e.g. hydrocarbons, H2) and wastes (e.g., CO2).

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MDT BRIDGE DECK CRACKING EVALUATION - INSTRUMENTATION AND MONITORING BASED SOLUTION

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ABSTRACT

Introduction

Montana Department of Transportation (MDT) commissioned WJE in 2016 to investigate the cause(s) of transverse cracking on concrete bridge decks in Montana. WJE provided recommendations to concrete mix designs, construction practices, and design considerations. Since implementation of the recommendations, MDT reported a notable decrease in early-age transverse cracking due to these changes, but then observed later age development of transverse cracks in some of their bridge decks.

Therefore, WJE was commissioned to perform additional investigations to further assess the benefits of the previous recommendations and to take a focused look at the later-age development of transverse cracking. WJE implemented a multi-disciplinary approach including literature review, field inspections, bridge deck instrumentation, laboratory evaluations, and finite element modeling.

Research

The research included a detailed literature review, inspections, instrumentation and monitoring of the bridge deck, as well as finite element analysis.

One concrete bridge deck was selected (Rarus/Silver Bow Creek Structure, Bridge D, located in Butte) to install instrumentation to monitor internal concrete temperatures, relative humidity, and strains at four separate locations. At each location, WJE embedded five thermocouples and three relative humidity probes at varying depths of the deck to obtain the temperature and relative humidity profiles. WJE also embedded vibrating wire strain gages (VWSGs) at each location. Ambient conditions were also monitored including temperature, relative humidity, wind speed, and solar radiation. After deck concrete placement, data from each gage was collected. The installed instrumentation system was, and currently still is, powdered by solar panels connected to rechargeable batteries. As of the date of this summary report, all installed gages are still being recorded, and the instrumentation has been in-place for a period of 24 months. The goal of the instrumentation was to better understand the impact of environmental changes on the internal deck temperatures, relative humidity and strains. The data collected from the instrumentation was also used to validate finite element modeling of this deck replacement. Nonlinear finite element (FE) simulations were conducted to help gain further insight into the effect of environmental factors and material properties on concrete deck stresses that lead to transverse deck cracking and to further refine previous WJE crack-mitigation recommendations.

The objective of the project was to identify the factors that have the greatest impact on the maximum tensile stresses within the concrete deck at early or later ages that pose the greatest risk to cause transverse cracking. Recommendations to mitigate transverse cracking were made.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BRIDGE 3D MODEL RECONSTRUCTION FROM UAV VIDEOS AND DAMAGE SEGMENTATION PROJECTION

Ji Dang[1]*

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ABSTRACT

The bridge structure can be recorded, measured, detected, diagnosed, and managed better in both maintenance and post disaster inspection. Recent technology makes it possible and easier to reconstruct bridge structural 3D point cloud and textured model using general purpose UAV with optical camera. Structure from Motion can be applied using frames from video combined with UAV sourced GPS Exchangeable image file format (Exif). However, unlike riverbank or dam, the bridge structure reconstruction is quite difficult using UAV and Structure from Motion methods as it is important to fetch information on its side and under surface. Thus, not only images token from above, but side view and under view photos are needed. And they must be aligned properly to prevent disturbances in the final model product. In this study the reason and some basic treatment in flight path design, such as flight high and frame intervals combination of far and close view, for miss alignment of image photos from UAV videos for bridges was discussed. With the implementation 2D image segmentation the projection of damage in 3D model and its application was also proposed for a next generation bridge maintenance platform. The recent improvements of multi damage segmentation including background reinforcement learning and human in the loop and their advance in practice of a few real bridge damage detections were also introduced.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BRIDGE STRUCTURE MAINTENANCE AND DISASTER MITIGATION USING UAV AND AI-HUMAN INTERACTION

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ABSTRACT

The recent happened 2024 Noto Peninsula earthquake reminded us again about how important the bridges in urban transportation are. The UAV based bridge inspection, damage detection can haste the diagnose and decision-making process in both effective scheduled maintenance and emergency actions after large scale disasters. In where, the AI based damage detection can further fastener the process, increase the accuracy and improve the quality. However in most of case, the AI trained by some prepared data-base can only performance good in the testing data set, once test it in a real structure inspection mission, there are great noise and unfortunate errors happens. To improve the real word accuracy of damage detection AI from UAV images, the AI-Human interaction progress can be considered. This method is to train a Deeplabv3+ or other semantic segmentation models by standard damage annotated image data, and training it again before use it to real bridge UAV videos by a few background non annotated images to let the background looked familiar to the model. The background reinforced training of UAV images resulted in improved detection accuracy. It is considered that this is because the model learned the characteristics of the bridge and the information around the bridge from the UAV image. After that, by creating a 3D damage model using the image that the damage detection was performed, we proposed a new utilization method of the 3D model.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMAGE BASED AUTONOMOUS CORROSION DETECTION IN STEEL STRUCTURES

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ABSTRACT

Periodical health monitoring is crucial for the structures, especially those that are made of steel due to the susceptibility to environmental corrosion. Engaging an inspector is mandatory for the currently practiced non-destructive inspection methodology. One of the problems associated with this inspection system could be inaccessibility to the defective region which might lead to undetected corrosion. The development of an autonomous methodology for corrosion detection became essential to mitigate this issue. This study presents the performance of conventional image processing and deep neural networks for extracting corroded pixels by semantic segmentation. For both methodologies, appropriate datasets were generated with the images from the in-service steel structures. Later, ten representative images were annotated for the conventional image processing method. The authors implemented a preprocessing method including histogram equalization, color space transformation, and brightness optimization to confirm the dataset's quality. After preprocessing, an algorithm was developed to separate the region of interest from the background. Finally, morphological operations such as binarization and edge detection were applied and the performance of the model was evaluated in terms of correct prediction. The authors revealed that the accuracy of the image processing method was subjected to the user-defined threshold values making them subjective to human involvement. For this reason, the authors evaluated the performance of an Encoder-Decoder network (UNet) architecture with different deep and shallow networks as backbones for autonomous segmentation of corroded pixels from the images. The authors developed a semantically segmented dataset with 2000 images and 2000 masks for the deep neural networks by applying several augmentation techniques. The performance of neural networks for different training modes was also investigated. DenseNet121 and EfficientNetB7 were first used as the backbone of the encoder part in the transfer learning mode. EfficientNetB7 reported the highest mean intersection of union (IOU) 95.6% which was incomparable to the IOU (57.3%) obtained by the image processing method. In the fully trained mode, ResNet34 and UNet both reported a 94% true positive rate (TPR) which was also significantly higher than the TPR (66%) achieved in the image processing method. Depending on the network architecture deep neural network might need 5-14 hours of training time for once, which was not required for the conventional image processing method. However, due to automation in processing steps inside the complex networks, the investigated deep learning models detected the corroded pixels in approximately 2 seconds which was not feasible for the semi-automatic image processing method.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACCELERATION AND STRAIN DATA FUSION TECHNIQUE FOR DISPLACEMENT ESTIMATION OF DYNAMIC SYSTEM

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ABSTRACT

Displacement plays a crucial role in structural health monitoring (SHM) of structural systems subjected to time-varying dynamic loads. However, due to the inconvenience associated with the direct measurement of displacement during dynamic loading and the high cost of displacement sensors, the use of displacement measurements often gets restricted. In recent years, indirect estimation of displacement from acceleration and strain measurement data has become very popular. Accurate estimation of displacement from acceleration and strain data requires data fusion techniques. Existing data fusion techniques mostly rely on system properties like mode shapes and have the inherent limitation of applicability being restricted to relatively simple beam-like structures. In this work, a Kalman Filter-based algorithm that does not use any system information has been developed for the acceleration and strain data fusion. For data fusion, one needs to estimate displacement from measured strain data. Estimation of displacement from noisy strain data poses a major challenge due to ill-conditioning of the inverse problem, which only estimates the displacement to a constant scale. To address this problem, a Kalman Filter-based algorithm is developed, which uses data fusion of estimated displacement from both acceleration and strain measurement to get accurate displacement estimate for the structure under dynamic loading. The method was validated on a numerically generated dataset from the finite element model of a tapered beam subjected to dynamic excitation. The major advantage of this technique is that there is no need of system information and the data fusion is performed using measured signals only. For practical applications, this data fusion technique can be used to calculate the displacement response of complex structural systems like wind turbine blades and helicopter rotor blades subjected to dynamic loading.

A HYGRO-THERMO-CHEMICAL DAMAGE PLASTICITY MODEL FOR CONCRETE IN 3D PRINTING APPLICATIONS

Dipankar Das[1] and Petros Sideris[1]*

[1]Texas A&M University

ABSTRACT

Construction 3D concrete printing is emerging as a transformative automated construction practice due to its capability to produce topologically optimized, lighter, and robust structures meeting strength and serviceability criteria along with lesser manpower requirements, which in turn can yield cost effective structures. In the case of concrete printing, further minimizing cost is associated with the rapidity of printing, which is mostly limited by the stability of the fresh prints. In fact, rapidly printed elements often collapse during printing or shortly after the printing. The stability of 3D printed elements and structures depends on the evolution of the mechanical properties of concrete over time, during and after printing. Thus, a concrete material model which can reproduce observed time dependent multi-axial stress and strain states of fresh concrete and its transition to the hardened state is needed to accurately predict the collapse at earlier states and strength at 28 days. This presentation proposes a new concrete damage plasticity (CDP) model considering the evolution of major model parameters, such as yield strength, ultimate strength and strain at ultimate strength, over time. Specifically, these model parameters vary based on an aging degree which represents the curing process and the overall progression of all binder reactions on the basis of a hygro-thermo-chemical (HTC) model. The constitutive material models, both the HTC and CDP, are formulated in rate form in order to account for the varying aging properties. The CDP model adopts separate tension and compression damage and a modified form of Lubliner's yielding with isotropic hardening/softening. The model parameters of the HTC and CDP models have been calibrated and validated with existing experimental data. This research study is the first step towards the development of a continuum concrete material model suitable for analyzing and designing the printing process for various 3D printed elements and predicting their 28-day strength. Next steps will include integration of viscoelastic responses. The broader goal of this research is to support analysis and design of 3D printed structures by the structural engineers.

Phase change materials (PCMs)-based multifunctional architected construction composites
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INFLUENCE OF MICROENCAPSULATED PHASE CHANGE MATERIALS (PCMS) ON THE FREEZE-THAW RESPONSE OF CONCRETE

He-Wen-Xuan Li[1], Rakesh Paswan[1] and Sumanta Das[1]*

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ABSTRACT

This study explores the influence of microencapsulated phase change materials (PCMs) on the freeze-thaw durability of concrete. Employing a finite element analysis (FEA)-based multiscale numerical simulation, the research assesses how PCMs affect the thermal response and influence freeze-thaw damage in concretes. These simulations integrate the latent heat characteristics of PCMs and apply continuum damage mechanics to quantify the extent of freeze-thaw damage. Results indicate a significant reduction in freeze-thaw-induced deterioration in concrete, attributed to the efficient thermal regulation provided by the PCMs. Further, the study introduces a neural network (NN)-based predictive model, constructed from a comprehensive dataset that includes variations in key design parameters like PCM volume fraction, transition temperature, and latent heat. This model, offering a computationally efficient alternative to intricate simulations, enhances understanding of the physical principles underlying the freeze-thaw resistance imparted by PCMs and clarifies the interactions among design parameters in determining concrete durability. Overall, this research not only demonstrates the positive impact of PCMs in improving concrete's resistance to freeze-thaw cycles but also advances material design, suggesting a promising direction for enhancing concrete durability in cold-weather environments.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SOLVING LARGE-SCALE INVERSE PROBLEMS WITH COUPLED DEEP GENERATIVE MODELS

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ABSTRACT

Bayesian inference is commonly used for solving inverse problems because it is useful for quantifying uncertainties. However, applying Bayesian inference to inverse problems of practical interest is challenging, especially when summarizing prior knowledge into informative priors and sampling high-dimensional posteriors. Deep generative models have recently shown tremendous potential for probabilistic modeling and inference. Leveraging the respective capabilities of two types of generative models—generative adversarial networks (GAN) and normalizing flows—the present work proposes a novel modular Bayesian inference framework. The proposed framework utilizes the intrinsic dimension reduction and superior sample generation capabilities of Wasserstein GANs to define a data-informative low-dimensional prior distribution. The generator of the trained Wasserstein GAN provides the injective map necessary for likelihood computations, transforming realizations from the low-dimensional latent space to the high-dimensional ambient space. The normalizing flow approximates the posterior distribution in the low-dimensional latent space via variational Bayesian inference. The normalizing flow offers a map that can transform realizations from the low-dimensional prior to corresponding realizations from the low-dimensional posterior. Thus, after training both generative models, one can generate any number of realizations from the latent posterior without additional computational effort to compute posterior-predictive quantities. The proposed framework uses a two-stage decoupled strategy to train both generative models sequentially. The symbiosis between both generative models allows us to overcome the above mentioned challenges. GANs offer a route to develop data-informative priors. At the same time, normalizing flows helps carry out variational inference, thereby avoiding recourse to Markov chain Monte Carlo methods that do not perform well on high-dimensional inverse problems. This work demonstrates the efficacy and flexibility of GAN-Flow on various physics-based inverse problems of varying ambient dimensionality and natures of prior knowledge using different types of GANs and normalizing flows. Notably, one application considers a 65,536-dimensional nonlinear inverse problem of recovering a signal from sparse and noisy measurements of the magnitude of its Fourier transform.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HARNESSING INSTABILITIES IN BIO-INSPIRED HIERARCHICAL TAPE SPRINGS

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ABSTRACT

This study investigates the mechanical properties of a family of bio-inspired tape springs, prompted by notable characteristics observed across three hierarchical levels. The first level explores a traditional curved tape spring capable of snapping instabilities, which is not evident in a flat spring. The second level takes cues from carinae-patterned telson of mantis shrimps, featuring a unique ridge pattern with outstanding energy-absorption capabilities akin to withstanding a .22 caliber bullet impact. This ridge pattern serves as the topological basis for enhancing the energy dissipation in tape springs. Leveraging insights from plant leaf venation patterns, second-order hierarchical tape-spring designs were engineered using machine learning and genetic algorithms, featuring multiple tailored ridges to meet specific mechanical requirements. The third hierarchical level is influenced by the flexible radula of the gumboot chiton, known for its ability to crush hard rocks along with its magnetite tricuspid teeth while feeding on algae. Through advanced computational modeling and rigorous experimental testing using specially designed novel rigs that can test bistable specimens under pure bending, this study comprehensively examines the performance of these hierarchical tape springs, offering valuable insights for their development across various applications, including soft robotics, energy-dissipating systems, lightweight structures, and fail-safe mechanisms.

QUANTUM HORIZONS FOR COMPUTATIONAL MECHANICS

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ABSTRACT

Quantum annealers, while adept at optimization problems, are often constrained by their specificity to problem types and the requirement for a substantial number of qubits for intricate tasks. Conversely, gate-based quantum computers exhibit versatility in a broader range of algorithms, including those pertinent to linear systems and differential equations, essential in computational mechanics. These systems are anticipated to deliver exponential improvements in efficiency and precision. However, challenges in scalability and the necessity for advanced error correction remain barriers to their full potential. We will explore these challenges, the current state of quantum computing technology, and its prospective impact on computational mechanics, heralding a new era of quantum-enabled problem-solving capabilities in the field.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RELIABILITY ASSESSMENT OF WIND TURBINE TOWERS CONSIDERING THE CUMULATIVE FATIGUE DAMAGE

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ABSTRACT

Wind turbine towers are structures continuously subjected to wind-induced dynamic forces. As a result of frequent exposure to these cyclic loads, structural reliability may be modified over time. In order to evaluate the evolution of reliability during the life cycle of a wind turbine tower, a fatigue analysis is required in order to consider the accumulated damage to the structure. However, the main obstacle to reliability assessment is the high computational cost associated with numerous nonlinear analyses, particularly when dealing with a large set of structural models. In this study, the use of Artificial Neural Networks (ANNs) is proposed to predict the damage index and the reliability index for medium-height wind turbine towers. The proposed methodology is divided into three distinct phases. In the initial stage, 15 incremental dynamic analyses (IDAs) are performed on a predefined set of structural models to determine their structural reliability. In the second stage, a fatigue analysis is carried out for each of the structures studied under the assumption that damage occurs at the base of the support tower. Finally, ANNs are trained to obtain a network capable of predicting the reliability index as a function of time and fatigue damage percentage. Furthermore, the results demonstrate that ANNs are powerful tools for solving complex engineering problems (reliability and fatigue) with acceptable accuracy.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING LARGE DEFORMATION SOIL LOADING AND FAILURE UNDER UNDRAINED CONDITIONS USING A MESHFREE APPROACH

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ABSTRACT

While the finite element method (FEM) is commonly used for undrained analyses of soils and engineered earth structures, the accuracy of traditional FEM is reduced for problems involving large deformations. Such problems arise whenever modeling the post-failure behavior of a particular structure or system is of interest. An alternative to FEM is smoothed particle hydrodynamics (SPH), a meshfree continuum-based particle method which has been successfully applied to model the elastoplastic behavior of geomaterials over large deformations. We propose a one-particle two-phase penalty-based formulation for handling undrained loading conditions with SPH and use it to analyze the propagation of reverse faults through fluid saturated clay deposits and the rupture of strike-slip faults across earthen embankments. Because of the short temporal duration of the fault rupture process, excess pore pressures that build up during the rupture do not have time to dissipate prior to the end of propagation. This fact makes the propagation of faults well suited for analysis under undrained loading conditions. In this study the soft muds and clays comprising the soil deposits are modeled with the Modified Cam Clay (MCC) constitutive model due to its suitability for capturing the buildup of pore pressures under compression, using a variation of the MCC closest point projection return mapping algorithm tailored to the SPH method recently developed by the authors. Ongoing research and recent results will also be presented and discussed.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF LOADING PROTOCOL FOR HURRICANE WIND PERFORMANCE TESTING OF DEFORMATION-CONTROLLED MWFRS MEMBERS

Baichuan Deng[1] and Teng Wu[1]*

[1]University at Buffalo

ABSTRACT

The wind design of buildings is moving forward to the performance-based wind design (PBWD) methodology, which allows for nonlinear responses in deformation-controlled MWFRS (Main Wind Force Resisting System) members. To ensure the structure meets the desired performance objectives, the wind-induced nonlinear response analysis becomes significant. The nonlinear models (backbone curves) of structural components currently utilized in the wind-induced nonlinear response analysis mostly refer to those developed in seismic engineering (based on seismic loading protocol), essentially due to the lack of rational wind loading protocols. Hence it is very important to establish loading protocols for extreme wind performance cyclic testing of structural components. In this study, a hurricane wind loading protocol design framework is proposed, consisting of wind hazard module, structural modeling module and component demand analysis module. Considering the extremely high computational cost of the high-fidelity structural model in the statistical-based loading protocol development framework, a simplified version is developed to improve the efficiency. Case studies are performed for the design of loading protocols of the coupling beam and shear wall in tall concrete buildings based on the developed framework.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SELF-STRUCTURED IMPORTANCE SAMPLING FOR CHANCE-CONSTRAINED OPTIMIZATION

Sai Rakshith[1], Anand Deo[2], Karthyek Murthy[3], Anirudh Subramanyan[4] and Shanyin Tong[5]*

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ABSTRACT

Chance constraints naturally emerge in systems where reducing risk is crucial, particularly those exposed to high-impact but rare events such as natural disasters, infrastructure failures, and financial crashes. However, the rarity of such events renders the solution of chance-constrained models impractical using naive Monte Carlo methods. Importance sampling can be a viable solution method in such cases, as it employs an alternate probability distribution to generate samples more frequently from rare-event regions. Nonetheless, the challenge of selecting an appropriate alternate distribution that is effective for all decision variables across various problems remains unresolved. Most existing strategies are problem-specific, necessitating an in-depth understanding of the system's dynamics. Our work adapts the self-structured importance sampling (SSIS) method, recently proposed by Deo \& Murthy, to develop a new algorithm for solving chance-constrained problems. This method transforms samples generated through naive Monte Carlo to samples that more accurately represent rare region behavior and can be universally applied across a wide range of constraint functions and probability distributions. Our results demonstrate that the proposed algorithm can substantially outperform Monte Carlo sampling in terms of both feasibility and optimality, even with small sample sizes.

NUMERICAL MODELING OF THE DEPLOYMENT MECHANISM OF A METALLIC PLATE-LATTICE SPACE FRAME

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ABSTRACT

From folded furniture and stairs to corrugated roofs and composite steel decks, cut and folded sheet metal arises in different civil construction settings to take load-carrying functions. Origami and kirigami-inspired structural components have the potential to enable more efficient production of load-bearing systems while reducing waste and transportation costs. To design these systems, it is essential to understand their behavior during the reconfiguration from their flat to their deployed state. The present work focuses on understanding the deployment mechanics of a kirigami system fabricated from a single sheet of metal. Once adjacent unit cells are deployed from a periodic cut pattern, they connect side by side to form a plate-lattice space frame. The product has a primary surface consisting of the original flat sheet with cuts, a secondary surface of adjacently deployed and connected cells, and the legs that connect both surfaces. Like expanded metal, reduced cross-sections at the legs concentrate the deformations produced by deploying the system, forming localized hinges near the primary and secondary surfaces. We use nonlinear finite element analysis with sequential quasi-static steps and beam elements to simulate the deployment mechanism of a sheet with a square grid cut pattern. The simulations are performed using Abaqus/Standard. We first deploy the central portions of unit cells called hubs using out-of-plane prescribed displacements. Then, we use axial connector elements to reduce the distance between vertices of adjacent units to form a fully connected secondary surface. We identify and present the scaling laws of the deployment loads for different metal sheet thicknesses and corroborate load-displacement simulation results with experiments from previous work [1]. The developed study aims to be used to foster the design of high-performance load-carrying kirigami structures.

[1] I. M. de Oliveira, E. M. Sosa, E. Baker, and S. Adriaenssens, “Experimental and numerical investigation of a rotational kirigami system,” Thin-Walled Structures, vol. 192, p. 111123, Nov. 2023, doi: 10.1016/j.tws.2023.111123.

THE LOW-TEMPERATURE PERFORMANCE OF AN ASPHALT BINDER MODIFIED BY THE SUB-EPOXIDIZED SOYBEAN OIL FOR COLD REGION APPLICATIONS

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ABSTRACT

The extreme weather conditions in cold, nordic, and arctic regions impose several challenges for asphalt pavement performance due to temperature-related stresses and cracking (Hjort et al., 2022). Investigations about the improvement of low-temperature performance of asphalts include using innovative materials as additives, which the application of biomaterials can promote more efficiency in the use of resources, reducing the dependency on fossil fuels (Yaro et al., 2022). Soybean oil products have shown multiple benefits as asphalt modifiers, such as reducing the aging effects, incrementing flexibility and elasticity, and changing the crack resistance due to modifications in glass transition temperatures (Elkashef et al., 2019). Therefore, this study investigated the asphalt binder low-temperature performance after the modification of a sub-epoxidized soybean oil for cold regions applications. The biomaterial was added in three different percentages, in a 64-28 PG grade binder. The experimental plan included an assessment of the low-temperature stiffness and relaxation through the Bending Beam Rheometer (BBR), rotational viscosity, Linear Amplitude Sweep (LAS), Frequency Sweep (FS), and Multiple Stress Creep and Recovery (MSCR) tests. Also, the anti-aging properties of the modification were evaluated using the Fourier-transform infrared spectroscopy in short-term aged samples by the Rolling Thin Film Oven (RTFO) procedure. Results showed that the bio-oil improved the rheological behavior of the asphalt binder, increasing the m-value and reducing the creep stiffness to a broader range of low temperatures. The addition also exhibited a rejuvenating effect on oxidative aged samples. It was concluded that implementing innovative solutions, such as adding biomaterials in asphalt, can effectively address low-temperature changes, which is important to obtain resilient and long-lasting asphalt pavements in cold regions.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RISK ASSESSMENT FOR LARGE-SCALE TRANSPORTATION INFRASTRUCTURE USING TRANSITIONAL MARKOV CHAIN MONTE CARLO SAMPLING

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ABSTRACT

Risk assessment in large-scale, interconnected transportation infrastructure is crucial for ensuring efficient asset management and risk mitigation. However, the large number of system damage states exhibits the so-called network effects, which indicate that the system-level consequences are different from the sum of individual consequences of damaged assets. This challenge is further compounded by the potential presence of rare but impactful “grey swan" events that may dominate the system-level risk, but are difficult to sample with conventional methods. To overcome these challenges, this study proposes a novel approach based on Transitional Markov Chain Monte Carlo (TMCMC) sampling that enables efficient and effective risk assessment for large-scale infrastructure networks. Two types of analytical examples are designed to rigorously assess the performance of the proposed approach against conventional Monte Carlo simulation (MCS) and a non-simulation alternative called risk-bound (RB) method. The first set of analytical examples show that both TMCMC and MCS methods can perform well for systems with increasing asset numbers if no network effects are present in the system-level consequences. By contrast, the RB method is not able to accurately estimate the risk of systems with large numbers of assets. The second set of analytical examples further compares the performance of the TMCMC and MCS methods under the presence of grey swan events. The results show that TMCMC sampling outperforms MCS in this case. The proposed method is also used to analyze the entire Oregon highway network with 1938 vulnerable links with bridges, as a real-world example of large-scale transportation networks. Additionally, the samples from the TMCMC process are shown to provide valuable insights to risk-informed asset prioritization.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MOLECULAR DYNAMICS STUDY OF BIOPOLYMER COMPOSITES

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ABSTRACT

To better understand the hygro-mechanical behaviour of biopolymer composites, Molecular Dynamics combined with Grand Canonical Monte Carlo simulations [1] is used to model sorption and sorption-induced deformation and determine the mechanical properties of biopolymer composites. In this study, we first analyze the hygromechanical behavior of composite consisting of amorphous cellulose (AC) reinforced with crystalline cellulose (CC). Then we treat the composite with PEG as consolidant.

The AC+CC composite shows swelling-induced sorption and a mechanical weakening upon sorption. Due to the reinforcing effect of the CC fibre, the swelling and weakening of the composite in longitudinal direction is supressed. Additional sorption is found to occur in the porosity created by the misfit between CC fibre and matrix, leading to a reduction of the pullout shear strength due to breakage of AC-CC hydrogen bonds by the water molecules.

Pure PEG shows much higher moisture contents and swelling strains at high relative humidity compared to AC, what opens the question why PEG can be used as a consolidant. Our results show that when adding only a limited amount of PEG the sorption and swelling behaviour of AC is reduced. This reduction is attributed to the filling of a large part of the existing porosity in AC by PEG, as such preventing additional water sorption. Adding PEG in the AC+CC composite results in filling the gap between CC and matrix, leading to a reduction of the volumetric swelling and sorption, and an enhancement of the pullout shear strength. However, as PEG content increases, this positive effect is overruled by the hygroscopic nature of PEG at high relative humidity, resulting in unwanted excessive swelling and reduction of the pullout shear strength. A poromechanical model is developed describing the hygromechanical behaviour of AC+PEG mixtures showing an optimal PEG mass fraction of 15%.

This study was inspired by the treatment of waterlogged archaeological wood of shipwrecks, like the Varsa and Mary Rose, with PEG for its consolidation and stabilization, where PEG molecules replace the water making wood at museum conditions less susceptible to changes in humidity and able to sustain mechanical load.

[1] M. Chen, B. Coasne, R. Guyer, D. Derome, J. Carmeliet, Role of hydrogen bonding in hysteresis observed in sorption-induced swelling of soft nanoporous polymers, Nat Com., 2018 29;9(1):3507. doi: 10.1038/s41467-018-05897-9

New challenges in instabilities of shell structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC BUCKLING OF IMPERFECT SHELLS: MULTI-DEFECT INTERACTIONS AND STATISTICAL INSIGHTS

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[1]EPFL

ABSTRACT

Thin shell structures are pervasive across length scales, ranging from tiny pollen grains to large storage tanks. Due to their high slenderness ratios, shells experience a pronounced sensitivity to imperfections, making their buckling a compelling topic within the research community. Traditionally, this problem has been extensively studied by focusing on shells with a single, well-defined imperfection and quantifying their knockdown factor, κ—the ratio between the measured buckling strength and the corresponding classic prediction for a perfect shell. However, the canonical question concerning more realistic shells with multiple defects remains open and challenging: What are the critical buckling conditions for shells containing a distribution of defects, and how do potential defect-defect interactions influence these conditions? Here, we employ finite element simulations, validated against high-precision desktop experiments, to investigate the knockdown factor statistics of elastic hemispherical imperfect shells with random distributions of defects. First, we explore shells with two interacting defects, uncovering an interaction regime characterized by the critical buckling wavelength reported in the classic shell-buckling literature. Then, we focus on imperfect shells with multiple defects distributed lognormally and find that the resultant knockdown factors of such shells can be described by a 3-parameter Weibull distribution. This finding suggests that shell buckling can be regarded as an extreme value statistics phenomenon. Finally, leveraging the benefits of interacting defects on the buckling strength of shells with multiple defects, we systematically remove various percentages of the most severe defects, effectively increasing the knockdown factors of such shells. Overall, this talk aims to deliver a fundamental understanding of the probabilistic buckling of spherical shells and seeks to stimulate the development of innovative functional mechanisms derived from defect interactions.

AI-enhanced probabilistic reliability assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CALCULATING SIMULATION-ASSISTED DECISION BOUNDARIES UNDER UNCERTAINTY USING MACHINE LEARNING AND ADAPTIVE CLASSIFICATION

Jake Desmond[1], Wilkins Aquino[2], Andrew Kurzawski[1], Cameron McCormick[1], Clay Sanders[1], Chandler Smith[1] and Timothy Walsh[1]*

[1]Sandia National Laboratories
[2]Duke University

ABSTRACT

Difficult engineering problems encountered in the world often must assess the adequacy of a system to meet the demands of its operating environment. For instance, we may be interested in determining whether an electronic component that was designed for a particular automobile would survive the dynamic loads experienced. A typical approach for this problem would be to select regions where the system performs satisfactorily by using physics-based simulations to explore the parameter space under consideration. However, performing many high-fidelity simulations of realistic physical systems is oftentimes infeasible, especially if one wishes to integrate parametric uncertainty (e.g. material properties, boundary conditions, etc.) into the decision-making.

This acceptance-rejection assessment problem commonly found in reliability analysis can be cast as a binary classification task under uncertainty. Our goal is to develop a framework using Support Vector Machines (SVMs) to incorporate simulation-derived data points to determine whether a specified operating environment is acceptable. We have combined the classification ability of the SVMs with various adaptive learning algorithms, including a greedy based approach, those based off work of Basudhar and Missoum, as well as additional modifications to aid the classifier in detecting the boundary within the high-dimensional feature space. Our approach aggregates the deterministic and random variables into a single parameter space over which the adaptive SVM learns, allowing one to minimize the number of high-fidelity simulations needed while simultaneously exploring the input space. A final post processing step calculates conditional probabilities of failure. We demonstrate through several numerical examples the feasibility of the method and the different adaptive learning algorithms, and then verify our answers using Monte Carlo simulations.

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Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LONG SHORT-TERM MEMORY NETWORK BASED SURROGATE MODEL FOR PREDICTING FRACTURE IN METALS

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ABSTRACT

Ductile fracture is a common fracture-initiating mechanism observed in several industrial metals which is driven by the nucleation, growth, and coalescence of microvoids under evolving stress state and plastic strain. Several uncoupled, coupled, and micromechanics-based damage models are available in the literature that can reasonably predict ductile fracture in metals. Among the available fracture models, the micromechanics-based GTN model is widely used in the fracture community to predict fracture by tracking the nucleation, and growth in the void volume fraction until coalescence. The GTN damage model when implemented as a constitutive model in the finite element analysis requires calibration of nine model parameters from experimental results and/ or representative volume element (RVE) analyses. Employing the GTN model as a constitutive model is computationally expensive. For instance, a 2D axisymmetric model of a cylindrical notched specimen consisting of 56,319 linear quadrilateral elements with reduced integration (CAX4R) requires approximately 8 to 10 hours of simulation time using 4 CPU cores in ABAQUS® (Explicit).

The present study aims to develop a data-driven artificial deep neural network-based surrogate model to predict the load-displacement response of ASTM A992 structural steel specimens undergoing ductile fracture when subjected to monotonic tension loading. To this end, a Long Short-Term Memory (LSTM) based deep neural network with fully connected dense layers was trained. The GTN model was used to predict the fracture behavior in a series of test specimens. Subsequently, the LSTM network was trained using the load and displacement data extracted from the GTN fracture simulations of these test specimens. The load-displacement data of each test specimen extracted from the finite element analysis was discretized into 500 time steps among which the initial n time steps were available to the network as an input. The initial n time steps were used to predict the (n + 1) time step. Following this, the model was used to recursively predict subsequent x number of time steps using the previous predictions. The model was validated by predicting the load-displacement response of axisymmetric notched test specimens subjected to uniaxial tension tests. The prediction results along with the computational time savings and limitations of the proposed surrogate model will be discussed in the talk.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FINITE VOLUME BASED MULTI-CONTACT MODELING TO STUDY DETAILED MECHANICAL RESPONSE OF AN ELASTIC MATERIAL

Ranjan Dhakal[1], Philip Cardiff[2] and Stefan Radl[1]*

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[2]University College Dublin

ABSTRACT

Analysis of powder compaction plays an important role in many material processing applications, for example to guarantee the quality of metallurgical powders, pharmaceutical tablets production etc. Stress and contact heterogeneities are quite apparent and thus influences the thermo-mechanical behaviour especially in powder compaction or while handling of powders and grains. A classical continuum based method neglects the micro-scale response and an appropriate constitutive relationship is required to model the deformation. On this account, a detailed study on mechanical behaviour due to solid contact during collision and compression are quite significant. Thus, a new computational tool has been developed with an aim to model a multi-contacting systems. This is based on a penalty method and has been implemented in the finite volume based open-source software environment ‘foam-extend-4.0’.

In order to investigate such a process representing a granular material compression, a confined fixed domain with moving punches at the top and bottom, has been examined for particles with varying size and configuration. As a step of verification, the contact properties (e.g. force, stress, strain) result demonstrates a very good agreement with the analytical solution. In case of a one-to-one contact it has been recognized that a deformation of 30 percent of the particle radius shows a noticeable conformity on the predictions. Furthermore, this tool not only provides users to track multi-contact deformation for a dense particles system but also facilitates development towards coupling of other properties of interest (e.g. thermal contact) in an open source environment.

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[2] JO Hallquist, GL Goudreau, and DJ Benson. Sliding interfaces with contact-impact in large-scale lagrangian computations. Computer methods in applied mechanics and engineering, 51(1-3):107–137, 1985.
[3] Peter Wriggers and Tod A Laursen. Computational contact mechanics, volume 2. Springer, 2006.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDITIVE MANUFACTURING PROCESS MODELING WITH MULTI-OUTPUT GAUSSIAN PROCESSES

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[1]Idaho National Laboratory

ABSTRACT

In recent years, additive manufacturing (AM) techniques have gained significant interest across government agencies and nuclear industries due to their ability to produce complex structures in a shorter time, facilitating faster material developments. These techniques have the potential to change the paradigm of new material and component designs for nuclear applications, such as producing new alloys and graded materials, as well as innovative component designs for advanced nuclear reactors. The key challenge AM techniques face is controlling process conditions to obtain desired microstructures and properties for targeted applications. Idaho National Laboratory’s (INL) Multiphysics Object-Oriented Simulation Environment (MOOSE), specifically the MOOSE Application Library for Advanced Manufacturing UTilitiEs (MALAMUTE) software, provides an ideal platform for developing the multiphysics multiscale model to explore the intricacies of the microstructural evolution during the AM processes within a single framework. Considering that full-fidelity multiphysics models are computationally expensive, especially when these models have to be run numerous times under varied or stochastic process conditions, surrogate modeling with the aid of Multi-Output Gaussian Processes (MOGPs) is utilized for computational efficiency. Dimensionality reduction techniques are combined with MOGPs to significantly reduce their training time and improve their predictive performance. The predictive capabilities of MOGPs with dimensionality reduction is evaluated both in terms of the median prediction and the quantified uncertainties. Finally, the outlook for using MOGPs in AM process modeling in conjunction with active learning will be discussed.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NONLINEAR BASIC CREEP OF CONCRETE: INTERPLAY OF VISCOELASTICITY AND CRACKING-INDUCED DAMAGE

Rodrigo Díaz Flores[1], Christian Hellmich[1] and Bernhard Pichler[1]*

[1]Vienna University of Technology

ABSTRACT

When subjected to uniaxial compression, concrete exhibits a linear creep behavior provided that the stress is smaller than some 40% of the quasi-static strength, and a nonlinear creep behavior provided that the stress is larger. The influence of nonlinear viscoelastic phenomena and cracking-induced damage on nonlinear basic creep of concrete under uniaxial compression is investigated. The present contribution is devoted to the analysis of a multilevel nonlinear creep test carried out on a mature concrete by Rossi et al. [http://doi.org/c795rc], which included measurements of strain and of the creation of microcracks by means of the acoustic emission technique. The test is analyzed as follows. The linear creep behavior of the tested concrete is quantified based on the reported mix design, a validated multiscale model for nonaging basic creep of cement paste under water-saturated conditions, and a further upscaling from the level of the cement paste to the level of undamaged concrete by representing concrete as a matrix-inclusion composite with spherical aggregates embedded in a cement paste matrix. Inspired by the work of Acker and Ulm [http://doi.org/b55rnm], a creep reduction factor is introduced to account for a relative humidity smaller than 100%. Nonlinear viscoelastic properties are quantified based on the affinity concept, which amplifies the linear creep curve by a factor that increases with increasing load level, see [http://doi.org/dzsxwf]. The influence of microcracking is accounted for by means of a newly-introduced damage factor, which relates the creation of microcracks to an increase in the compliance of damaged concrete. The value of the damage factor is identified based on the experimental measurements. The model was able to reproduce the experiments very accurately, up to a stress level amounting to 75%. This confirms that nonlinear creep of concrete is primarily caused by viscoelastic phenomena in combination with cracking-induced damage. Further studies regarding the mechanics of concrete at the microscale are recommended to determine the dependence of the damage factor on the mix design.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING FLOOD DAMAGE TO RESIDENTIAL BUILDINGS AND CONTENTS WITH EXPLICIT UNCERTAINTY QUANTIFICATION FOR MORE INFORMED DECISION-MAKING

Mario Di Bacco[1], Pradeep Acharya[2], Daniela Molinari[3] and Anna Rita Scorzini[2]*

[1]University of Florence
[2]University of L'Aquila
[3]Polytechnic University of Milan

ABSTRACT

Detailed data on hazard, vulnerability and exposure are essential for implementing reliable flood damage models, which are key to support risk management decisions. Despite this importance, issues on data availability, accessibility and completeness may significantly induce large damage estimation uncertainty. This study builds on INSYDE (Dottori et al., 2016), a physically based multi-variable flood damage model for buildings, proposing an updated version (INSYDE 2.0) with an enhanced probabilistic treatment of missing input data and the inclusion of a new module for building contents (INSYDE-CONTENT). Although both models have been specifically conceived and validated for the Po River District, the framework can be successfully applied in other areas after a proper adaptation (Scorzini et al., 2022). In consideration of the high number of required input data, the model has a built-in function that replaces possible missing data with values sampled from probability distributions representative of the hazard and building features in the examined area. These distributions are derived from official data, numerical simulations and virtual surveys of houses listed in real estate websites for the region of interest.

The advantage of this option relies on informative outputs characterized by uncertainty bands, allowing a more informed decision-making compared to a single number resulting from deterministic models, which can sometimes convey a false perception of certainty.

This study was conducted within the RETURN Extended Partnership and received funding from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NOVEL TLCD-BASED WAVE ENERGY CONVERTER WITH DIELECTRIC ELASTOMER GENERATOR

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[2] *Univeristy of Palermo*

ABSTRACT

This paper introduces a theoretical and numerical study on a novel device for a wave energy converter (WEC) based on dielectric elastomer (DE) membranes. These are systems that can convert the energy of ocean waves into electricity by employing compliant polymeric generators that afford converting mechanical energy into electrical energy by exploiting the large deformations of elastomeric membranes. In this regard, the novel system combines the concept of oscillating water column WEC with an inflated circular diaphragm DE membrane. Further, a novel design of the WECs is proposed based on the use of the so-called Tuned Liquid Column Dampers (TLCDs), that is systems generally employed as vibration control systems usually designed as U-shaped containers full of water. The proposed novel device features strongly nonlinear dynamics due to the DE electro-hyperelastic response and the compressibility of the air volume comprised between the water column of the TLCD and the membrane. A lumped-parameter mathematical model of the proposed WEC is defined, and the coupled nonlinear equations governing the response of the system are determined. Finally, the optimal design of the system that maximizes the power extraction of the device is numerically investigated in the case of monochromatic waves over the typical frequency and amplitude ranges of sea waves, as well as under random excitations.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING OF THIN CYLINDRICAL SHELLS WITH GEOMETRIC IMPERFECTIONS UNDER COMBINED BENDING AND TORSION

Victoria Ding[1], Shahab Torabian[1], Sandor Adany[12] and Ben Schafer[1]*

[1]Johns Hopkins University
[2]Budapest University of Technology and Economics

ABSTRACT

Cylindrical shells with large diameter-to-thickness ratios (normally around 180) are widely used in wind turbine towers. Stability of these thin-walled shell structures is an essential concern, along with cross-section actions on wind turbine towers involving interactions of compression, bending, shear, and torsion arising from both environmental and operational load case conditions. Combined bending and torsion are commonly the dominant actions in the upper tower segments. The high diameter-to-thickness ratios of these cylinders make them highly imperfection sensitive, which means failure loads and failure modes are highly dependent on initial geometries of the cylinders. Though there have been extensive studies into the stability and design of cylinders subjected to isolated loading conditions (i.e. pure compression or pure bending), investigations into the structural response of thin-walled cylinders under combined bending and torsion remain scarce. To address the knowledge gap, an experimental and modeling study was conducted on the stability of cylinders under combined bending and torsion. A total of 48 cylinders with diameter-to-thickness ratios ranging between 127 and 320 were tested under varying bending and torsion combinations. To better understand how imperfections affect the buckling modes of these thin-walled cylinders, a 3D laser scanner was used to determine geometric imperfections of each test specimen prior to testing. Then finite element models of these cylinders with their real geometric imperfections were created by using their laser scanned data and compared to the experimental results. The cylinders' structural responses, including ultimate resistances, load-deformation characteristics, effects of imperfections, and buckling behavior are reported. These models capture the buckling strength and failure modes of thin-walled cylinders under combined bending and torsion and are used for developing reliable and efficient design approaches for such structural elements.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISTRIBUTED-VARIABLE-ORDER NONLOCAL ELASTICITY AND ITS APPLICATION IN COARSE-GRAINED MODELING OF HETEROGENEOUS NONLOCAL MEDIA

Wei Ding[1] and Fabio Semperlotti[1]*

[1]Purdue University

ABSTRACT

Existing nonlocal mechanics, such as Eringen's integral elasticity and strain gradient elasticity, are developed based on the assumption of homogeneous distribution of nonlocal effects. Therefore, current nonlocal elasticity theories have fatal theoretical drawbacks and are not capable of modeling micro/nanomaterials with heterogeneous nonlocal effects. To address limitations in existing nonlocal theories, this study presents an advanced fractional-calculus-based nonlocal elasticity by using distributed-variable-order (DVO) operators. As a general extension of conventional constant-order fractional operators, DVO operators possess advantages from both the distributed-order operators (the multiscale feature) and the variable-order operators (the evolutionary feature). The combined advantages make DVO operators more suitable for modeling heterogeneous nonlocal effects. A pairwise symmetric DVO nonlocal constitutive relation is defined to describe the heterogeneous nonlocal effects while ensuring the self-adjointness of deformation energy operators and the well-posedness of nonlocal formulations. The governing equations and associated boundary conditions are derived by applying variational principles. Coarse-grained finite element simulations are performed to validate the effectiveness of DVO nonlocal elasticity. Numerical results obtained from both elastostatic analyses and free vibration analyses have shown that the proposed DVO nonlocal elasticity can capture spatially varying nonlocal effects both accurately (due to the variable-order component in DVO operators) and effectively (due to the distributed-order component in DVO operators).

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SUSTAINABLE SEISMIC RETROFIT OPTIMIZATION FOR EXISTING REINFORCED CONCRETE STRUCTURES

Fabio Di Trapani[1], Antonio P. Sberna[1] and Josephine Carstensen[2]*

[1]Politecnico di Torino
[2]Massachusetts Institute of Technology

ABSTRACT

Seismic retrofitting measures for reinforced concrete structures are commonly linked with noticeable expenses, significant intrusiveness, and considerable downtime. Despite the urgent need to reduce CO2 emissions in civil engineering, the environmental impact is often overlooked in the design phase. Recent research has demonstrated that computational intelligence can effectively automate the seismic retrofit design process, optimizing it based on cost considerations. However, a minimum-cost design does not necessarily equate to low carbon emissions. In this context, this study proposes a framework utilizing genetic algorithms for optimizing embodied carbon in various retrofitting techniques. The Global Warming Potential (GWP) is used as a key metric for measuring the embodied carbon emissions associated with each retrofitting technique. The study conducts a case test on a typical non-seismically compliant reinforced concrete building structure. Optimization is performed, considering four potential retrofitting techniques (steel jacketing, concrete jacketing, FRP jacketing, and steel bracing). The optimal results are finally compared based on environmental impact and associated economic costs.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF CONSTRAINTS ON BRITTLE FRACTURE OF THICK STEEL ELEMENTS

Thanh Do[1]*

[1]Thornton Tomasetti

ABSTRACT

Inspired by recent brittle failures of massive steel structures, this paper discusses the net section failure behavior of thick steel elements and how it is addressed in current design codes. In common guidelines such as AISC, net section failure of a tension member is typically associated with ductile fracture when the stress reaches the material tensile strength. This is driven by the common underlying assumption that local yielding at the net section occurs, and the steel material has sufficient ductility to redistribute the elevated stresses near the stress raisers (e.g., holes, notches) to the surrounding materials. The ability to accumulate plastic deformations across the net section ensures a ductile failure behavior, as opposed to brittle fracture that is characterized by high stresses and limited plasticity. While the assumption of stress redistribution and plastic flow is reasonable for many practical applications, it does not necessarily hold when the structural component has a high degree of constraints, such as due to the high member thickness or intersecting welds of a built-up assembly. In these cases, accumulation of plastic deformations throughout the net section may not be possible (such as due to large hydrostatic stress component, and/or limited increase in strain). As a result, the component may fail in a brittle manner. To address the code limitation, this paper investigates the effect of constraints on the net section failure and assesses when common design assumptions are no longer valid.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIERARCHICAL DATA-DRIVEN MODELING OF HUMAN INTERACTIONS WITHIN SOCIAL INFRASTRUCTURE SYSTEMS

Maral Doctorarastoo[1], Katherine Flanigan[1] and Mario Bergés[1]*

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ABSTRACT

Modeling social interactions is paramount to the development of cyber-physical social infrastructure systems (CPSISs), which aim to improve social capital through the design and operation of infrastructure systems. For example, public open spaces are vital urban infrastructure providing opportunities for social and recreational activities. Well-designed public spaces enhance well-being, mental health, physical health, and socio-ecological benefits. Similarly, the physical state and organization of school buildings can influence student health, cognitive abilities, and academic performance. A detailed understanding of human-human and human-infrastructure interactions is key to predicting and enhancing the functionality and user experience within these systems. Despite the intimate coupling between social benefits and the state of infrastructure, there is no quantitative understanding of how to integrate and optimize social systems within cyber-physical systems to produce CPSISs. This research introduces a data-driven model for simulating social interactions in CPSISs, utilizing gestures, turn-taking, and other sensory data collected from the users' interaction habits. This approach aims to reflect the complex dynamics of interactions within infrastructure systems. The social interaction model employs imitation learning (IL) to mimic human social interaction habits based on sensory data, integrated within a hierarchical structure of imitation and reinforcement learning (RL) for modeling human behavior. This structure comprises a high-level IL to capture strategic decisions of agents and a low-level RL for detailed movements. IL's primary advantage lies in its capacity to train models directly from real-world sensed data, eliminating the need for extensive surveys or expert opinions. This hierarchical approach combines the real-world behavioral fidelity of IL with the dynamic adaptability of RL. Once social interaction is selected as the activity, the model intricately simulates interactions between agents. This framework addresses the limitations of traditional agent-based models (ABMs), which suffer from rigid, hand-crafted action rules that become overly complex in intricate settings and lack transferability to new environments. The effectiveness of our proposed framework is demonstrated using a conference room case study. We present the training process involving multiple agents with different goal combinations and detail a sample trajectory to showcase the agents' performance in social interaction. This illustrates the model's capability to realistically simulate human behavior in CPSISs, offering significant insights for future infrastructure design and management optimization.

Multi-fidelity methods and machine learning for uncertainty propagation, inference, and optimization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-FIDELITY MODELLING FOR DIGITAL TWINS OF FAST MANUFACTURING PROCESSES UNDER UNCERTAINTY

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ABSTRACT

Multi-fidelity methods combine low-fidelity models with high-fidelity ones through versatile model management strategies.[1] This enables a large area of applicability. One area, with a recent interest in multi-fidelity methods, are digital twins. A digital twin is a virtual representation of a physical process and is updated in real time according to changes the process experiences.[2] Additionally, the digital twin can control the physical process, which requires a trustworthy, fast-to-evaluate virtual model.

In manufacturing processes, such as resistance spot welding (RSW), the model updating and parameter optimization need to be equally fast as the process itself. This makes numerical models oftentimes prohibitively expensive, especially for nonstationary, highly non-linear, fast processes, such as RSW. Forming a welding nugget usually takes around 40-400 milliseconds with a total operation time of about one second. However, the corresponding FE-model, considering a thermally-electrically-mechanically coupled mechanism [3], has an evaluation time of multiple hours. Furthermore, uncertainty quantification is essential, because the process is highly sensitive to small changes in the operating environment. In addition to the FE-model, live diagnostic measurements, such as welding current and voltage, can be obtained at almost no cost. They can give more insights about the actual output than any deterministic model, especially if coupled with expensive, destructive sample measurements.

In summary, there is an expensive-to-calculate FE-model, which can provide an approximated estimation of the output quantity but does not include any process information. Then there is the easy-to-acquire measurement data, which contains those additional information and lastly, the accurate, expensive-to-measure process performance. We propose to fuse the different sources of information with a multi-fidelity surrogate model, that can reliably and in near-real-time predict the output of interest during the welding process.

In this contribution, the authors validate the model on an existing RSW-dataset and discuss the implementation of multi-fidelity in digital twins.

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Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-ENABLED PERFORMANCE IMPROVEMENT OF BUILDINGS LOCATED IN HIGH WIND HAZARD REGIONS

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ABSTRACT

Buildings located in high wind hazard regions are vulnerable to wind-induced excitations due to their high flexibility and low damping characteristics. To address this vulnerability, a thorough understanding of the role of façade systems is vital. This study introduced a data-driven methodology to predict the performance of tall buildings under varying wind conditions, considering the uncertainties related to wind dynamics and façade system implementations. The investigations utilized data obtained from wind tunnel tests on a tall building model equipped with shape-morphing façade systems. These façade systems acted as aerodynamic control surfaces, reducing wind load effects on the structures. A novel combination of machine learning algorithms and computational simulations formed the main contribution of this study. The algorithms were trained and validated using the data collected from wind loads and wind-induced responses. The outcome predicted the expected wind load and optimal façade system, while computational simulations provide detailed insights into the structural behavior under various wind conditions. Probabilistic models and sensitivity analyses were integrated into the developed platform to further quantify and address uncertainties in wind patterns and structural response characteristics. The obtained results indicated the effectiveness of this approach in accurately predicting building responses to diverse wind conditions, capturing the complex interaction between wind dynamics and structural response details. This is deemed a critical step towards more resilient urban structures and communities that rely on them.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATING GAIT BIOMECHANICS AND STRUCTURAL DYNAMICS TO ESTIMATE LOWER-LIMB JOINT MOTION FOR HUMAN GAIT HEALTH

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ABSTRACT

Quantitative estimation of lower-limb joint motion outside clinics is essential for early detection and rehabilitation tracking of neuromusculoskeletal disorders (e.g., Parkinson's) and mitigating trip and fall risks for older adults. Existing approaches involve monitoring devices such as cameras, wearables, and pressure mats, but have operational constraints such as direct line-of-sight, carrying devices, and dense deployment. To overcome these limitations, we leverage gait-induced floor vibration to estimate lower-limb joint motion (e.g., ankle, knee, and hip flexion angles), allowing non-intrusive and contactless gait health monitoring in people's living spaces. The primary research challenge is the high uncertainty in lower-limb movement given the limited information provided by the gait-induced floor vibrations, making it challenging for conventional data-driven models to estimate joint angles accurately. To overcome this challenge, we formulate a physics-informed graph to integrate domain knowledge of gait biomechanics and structural dynamics into the model. Specifically, different types of nodes represent heterogeneous information from joint motions and floor vibrations; Their connecting edges represent the physiological relationships between joints and forces governed by gait biomechanics, as well as the relationships between forces and floor responses governed by the structural dynamics. As a result, our model poses physical constraints to reduce uncertainty while allows information sharing between the body and the floor to make more accurate predictions. We evaluate our approach with 20 participants through a real-world walking experiment. Results show that our model has an average of 3.7 degrees of mean absolute error in estimating 12 joint flexion angles (38% error reduction from a Long Short-Term Memory (LSTM) baseline), which is comparable to the performance of cameras and wearables in current medical practices.

Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING THE EFFECT OF ENERGETIC SOFT SURFACES IN HIGHLY DEFORMABLE SOLIDS

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ABSTRACT

Superficial stresses in highly deformable solids significantly influence their overall mechanical properties at scales below a characteristic length. This length scale can extend up to several hundred micrometers in soft solids possessing a Young's modulus on the order of kilopascals. Classical continuum mechanics, viewed from a theoretical perspective, is inherently size-independent and thus does not incorporate a physical length scale. However, the characteristic length scale and the size-dependent response of the material can be effectively modeled in continuum frameworks by considering the energetic interplay between the bulk of the solid and its boundary. Currently, to what extent the superficial stresses in polymeric materials are strain- and time-dependent is being investigated through combined experimental and modeling approaches.

A fundamental challenge in understanding the behavior of soft materials at small scales is to elucidate the nonlinear effects that arise from complex surface stresses, including strain-stiffening, viscous effects, and surface flexural resistance. The primary focus of this presentation is to showcase an elegant computational framework designed for modeling highly deformable materials, characterized by (i) strain-dependent surface properties, (ii) surface viscoelasticity, and (iii) bending stiffness. We demonstrate that surface viscoelasticity can capture size-dependent dissipation in soft polymeric materials, thus introducing an emergent time scale. Furthermore, we illustrate how material surfaces contribute to emergent length- and time-scale effects, enhancing the creep and relaxation behaviors of the overall structure. We believe our methodology offers a robust computational basis for elucidating visco-elasto-capillary deformations in soft polymeric gels. Additionally, by incorporating flexural resistance into zero-thickness material surfaces, we identify a novel emergent characteristic length scale, originating from surface bending energetics.

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL AND EXPERIMENTAL VALIDATION OF AN UPLIFT FRICTION DAMPER FOR SEISMICALLY RESILIENT ROCKING WALL SEISMIC-FORCE RESISTING SYSTEMS

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ABSTRACT

There has been a growing interest in recent years by both researchers and industry in developing seismically resilient seismic-force resisting systems (SFRSs). This design approach typically involves the use of low-damage and/or replaceable structural fuses for inelastic seismic energy dissipation in combination with a frame/wall rocking system. In doing so, building structures with seismically resilient SFRSs are expected to have minimal residual drifts and would be rapidly repairable after a moderate to large earthquake. An uplift friction damper (UFD) for rocking wall SFRSs has recently been proposed. These friction dampers have enhanced seismic performance by using inclined friction interfaces (i.e., not colinear with the plane of loading) in combination with steel disc springs. This combination provides both energy dissipation and some self-centering characteristics. The first part of this presentation will present the basic kinematics of the UFDs along with the experimental results of two testing programs of a mass timber rocking wall equipped with the UFDs. The first testing program involved quasi-static component testing of a scaled rocking wall to validate the cyclic response. The second testing program validated the dynamic response of the UFDs installed on a test building with realistic boundary conditions subjected to simulated ground motions. The latter dynamic test program was a payload test phase of the NHERI TallWood 10-story mass timber building conducted at University of California San Diego’s 6-degree-of-freedom large, high-performance shake table. For this purpose, the UFDs were installed as added supplemental energy dissipation devices. The second part of this presentation presents challenges and solutions to the numerical modeling of the UFDs for the purpose of nonlinear response history analysis. In particular, a generalized numerical model implemented in the OpenSees structural analyses framework that could be broadly applied to the numerical modeling of a broad range of seismically resilient type friction dampers will be presented. The modeling scheme utilizes readily available elements (found in most commercial structural analysis software), eliminating the need and complexity of creating new material models. Illustrative examples using two distinctly different seismically resilient friction dampers are presented for validation of the proposed numerical modeling approach. The first comparison is made with the mass timber rocking wall with the installed UFDs noted earlier and compared with the quasi-static cyclic tests. The second validation example compares results of quasi-static uniaxial cyclic test of a Friction Spring Damper device that was recently conducted by others.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-OBJECTIVE PERFORMANCE-BASED RISK OPTIMIZATION OF STEEL STRUCTURES SUBJECTED TO SEISMIC ACTIONS

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ABSTRACT

Optimizing structural systems subject to seismic actions to minimize failure probability, repair costs, and injuries to occupants, significantly contributes to the resilience of buildings in earthquake regions. This study introduces a comprehensive framework for the multi-objective optimization of steel structures, incorporating the Performance-Based Earthquake Engineering (PBEE) methodology delineated in FEMA P-58 [1]. A selected set of ground motions, consistent with the seismic hazard intensity of interest, and a nonlinear finite element model, established using OpenSees, enable the assessment of the system's dynamic response. To address the computational complexity related to evaluating the probability of failure of the system during an optimization iteration when using the PBEE methodology for assessing performance, this study introduces metamodeling techniques as a substitute for the original high-fidelity nonlinear finite element model. In particular, Kriging is employed to approximate both the median and standard deviation of the Engineering Demand Parameters (EDPs) for any given value of the design variable vector. The parameters of the Kriging metamodels are derived from nonlinear dynamic analyses performed using the original high-fidelity model and an optimal sampling plan obtained through Latin Hypercube sampling. Under the assumption of a lognormal distribution, the metamodel is then used to approximate the median and dispersion necessary to calibrate the fragility functions modeling collapse and repair costs for any given value of the design variable vector. By leveraging the metamodels, a risk-based optimization scheme is defined that allows system performance to be described by the FEMA P-58 PBEE methodology. The scheme is illustrated on a full-scale case study consisting in the multi-objective optimization of the buckling-restrained braces of a steel seismic force-resisting system in terms of expected losses and construction costs. It s shown that the proposed risk-based optimization scheme allows for the effective balance between construction costs with expected financial losses from earthquakes, leading to the enhancement of the seismic performance of the system.

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Probabilistic learning, stochastic optimization, and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC LEARNING AND BAYESIAN INFORMATION FUSION FOR THE CONSTRUCTION OF A BUILDING DIGITAL TWIN

Jingwen Du[1], Ibrahim Ahmed[1], Vinay Dhanvada[1], Gbandi Nikabou[1], Pranav Karve[1] and Sankaran Mahadevan[1]*

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ABSTRACT

This presentation describes the development of a novel health monitoring and building risk management approach in coastal areas by pursuing a probabilistic digital twin concept. The work integrates models in multiple disciplines such as wind forecasting, wind load prediction on the building, and structural response analysis. The quantity of interest that is predicted and monitored is mechanical strain, and the digital twin model of the system (i.e., wind load plus structure) is updated continuously as new data is acquired, and provides a probabilistic prognosis of the structural response in order to support future risk management decision-making.

The pursued digital twin approach consists of four essential steps: wind forecasting, fluid-structure interaction modeling, structural response analysis, and model updating using monitoring data. In the first step, historical data on NOAA weather forecasts and anemometer-based wind speed/direction measurement are first used to train probabilistic machine learning (ML) models that forecast wind speed (mph) and direction (degrees) utilizing previous observations. Specifically, we investigate two types of prediction model forms: autoregressive integrated moving average (ARIMA) models and long short-term memory (LSTM) models. ARIMA models perform better for shorter prediction windows (minutes), while LSTM models perform better for longer-term, hourly forecasting. In the second step, we construct a three-dimensional computational fluid dynamics (CFD) model to simulate the predicted wind flow and the fluid-structure interaction, taking into account the distinctive topography surrounding the building with a spectrum of boundary conditions. The third step builds a finite element (FE) model to analyze the structural response.

Two surrogate models are constructed for the CFD and FE analyses respectively, to alleviate the computational burden of executing these high-fidelity physics models. These models enable the prediction of wind pressure on the building and then the mechanical response at the building locations of interest given the forecast wind conditions. In the fourth step, a probabilistic digital twin using a Bayesian network is constructed that encapsulates the joint probability distribution of all relevant variables. The digital twin model parameters are updated through Bayesian calibration, along with the model discrepancy term, using real-time measurements. The model refinement proceeds in a recursive manner from one time instant to another, showcasing the importance of bi-directional flow of information for the digital twin's effectiveness. The proposed approach is demonstrated for application to an aircraft hangar building in a coastal area.

Advances in vibration and structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEQUENTIAL OPTIMAL CONTROL: A GLOBAL OPTIMAL STRUCTURAL CONTROL OF FORCED VIBRATION SYSTEM

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ABSTRACT

Among various control strategies, the optimal control forms theoretical basis for classical control theory, and has been studied at the very early stage of structural vibration control. However, due to misunderstanding of classical optimal control theory, two very famous, early models of optimal structural control expressed structural vibration control in a model with a separate term of earthquake excitation, confusing the optimal structural control model. In fact, the earthquake excitation is regarded as diturbance, which is not included in classical control theory. If the structural vibration control is modeled with separate earthquake excitation term in the state space expression, the traditional Ricatti equation cannot be derived in its conventional form, and the control force can not be solved analytically, even if the earthquake signal is known in advance.

On the other hand, there really exists a practical need for calculating the control forces for the optimal structural control problem subjected to earthquake excitation. The control forces in a seismically controlled structure can not be easily obtained after the total control force is solved from Riccatti equation, because the earthquake excitation and the control force forms a confused output – input relationship. even if the earthquake signal is known.

This paper clarified some mathematical imperfections in the early models of optimal structural control by comparing to the theoretical model of optimal control of seismic isolated structure based on classical control theory, and proposed a general model for global optimal control of structures subjected to earthquake excitation, and derived a mathematically rigorous extreme value condition for optimal control of structures. The proposed model and algorithm can be used as a general method for solving the optimal control force in any forced vibration system. Due to the inability of obtaining an analytical solution, the calculation of the optimal control force has been realized using state transition algorithm. The model can be seen to be mathematically rigorous, because it is derived from optimization method with variation, and the result of optimal control force can be regarded as accurate solution apart from the arithmetic errors induced by numerical operation.

Key words: optimal structural control; smart isolation; base isolation; vibration control of structures

Repair and assessment of deteriorating critical infrastructure
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATIONAL ANALYSIS OF REPAIR AND REHABILITATION OF AGING UNDERGROUND CAST-IRON PIPELINES WITH CURE-IN-PLACE-PIPE LINER

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ABSTRACT

During the early 20th century, the United States experienced rapid industrial and economic growth, leading to the construction and operation of a significant number of underground pipelines. Most of these pipelines, for example, the sewer systems built in the early 20th century, are now in need of repair. Also, as of 2017, there were 26,060 miles of gas distribution lines in the U.S. that have been in service for over 100 years. As the most historically used metal material in underground pipes, cast iron has been widely employed in water, sewer, gas, and oil pipelines. However, corrosion, cracks, and damage have been observed in aging cast iron pipes, leading to severe outcomes. To repair and rehabilitate the aging pipelines, a trenchless method – Cured-in-Place-Pipe (CIPP) lining – was introduced. CIPP liner involves a hollow cylinder containing fabric material impregnated with a cured thermosetting resin, which is then installed on-site using inversion or pulled-in-place techniques. In this study, we aim to analyze the aging underground cast-iron pipes before and after CIPP liner rehabilitation through computational analysis. A three-dimensional (3D) finite element analysis (FEA) model is developed to simulate the aging cast-iron pipe. A parametric study is performed to evaluate the effect of various parameters including external and internal loads, geometry, hole size in damaged pipes, and interfacial conditions. In addition, sensitivity analysis is conducted to determine the most critical factors and provide information on optimal liner material design under different scenarios. The simulation results indicate that external loads, such as soil and traffic load, do not significantly affect the performance of aging pipes, while internal pressure exhibits a substantial impact, especially for high-pressure distribution pipelines. We also investigate the curved pipes rehabilitated by CIPP liners and calculate the stress concentration inside the pipe elbow. Moreover, we evaluate the combined effect of the critical factors, finding that the stress on the corrosion hole at the inside curve of the pipe elbow is three times higher than the stress in an intact pipe. The analysis results presented in this study could be used as a guideline for repairing and rehabilitating aging underground cast-iron pipelines with minimal environmental disruption and optimal CIPP liner material design.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FINITE ELEMENT BASED COHESIVE ZONE MODELS FOR HYDRAULIC FRACTURE PROPAGATION IN GLACIERS AND ICE SHELVES

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ABSTRACT

Crevasses are predominantly mode I fractures penetrating tens of meters deep into grounded glaciers and floating ice shelves that are hundreds of meters thick. Hydraulic fracture (or hydrofracture) can promote the propagation of water-filled surface crevasses in grounded glaciers and, in some cases, lead to full-depth penetration that enhances basal sliding by altering subglacial hydrology. To better understand the physical factors (e.g., glacier geometry, material properties, and environmental conditions) controlling the full-depth propagation of water-filled crevasses, it is necessary to employ advanced fracture models for representing the quasi-brittle fracture process in glacier ice. With this in mind, we formulated two finite element based cohesive zone models (CZMs) for hydrofracturing of crevasses in floating ice tongues and grounded glaciers, by idealizing the conditions in Antarctica and Greenland.

In this presentation, first we will present a CZM to capture quasi-static hydrofracture propagation in nonlinear elasto-viscoplastic ice medium (Gao et al., 2023). We will show several numerical studies to explore the parametric sensitivity of surface crevasse depth to ice rheology, cohesive strength, density, and temperature. We find that viscous (creep) strain accumulation and depth-varying density and temperature of ice promote surface crevasse propagation, which is not captured by existing linear elastic fracture mechanics models. Next, we present a CZM that describes time-dependent fracture propagation in an idealized glacier causing rapid supraglacial lake drainage. A novel two-scale numerical method is developed to capture the elastic and viscoplastic deformations of ice along with crevasse propagation (Hageman et al., 2023). The fluid-conserving thermo-hydro-mechanical model incorporates turbulent fluid flow and accounts for melting/refreezing in fractures. Applying this model to observational data from a 2008 rapid lake drainage event indicates that viscous deformation exerts a much stronger control on hydrofracture propagation compared to thermal effects. This finding contradicts the conventional assumption that elastic deformation is adequate to describe fracture propagation in glaciers over short timescales (minutes to several hours) and instead demonstrates that viscous deformation must be considered to reproduce observations of lake drainage rate and local ice surface elevation change.

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Toward data-driven approaches for uncertainty quantification and propagation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A COMPARATIVE STUDY OF BI-FIDELITY TRANSFER LEARNING OF BAYESIAN NEURAL NETWORKS

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ABSTRACT

Neural networks have been an effective approach for defining the dynamics of nonlinear systems. With sufficient data, neural network models are capable of learning the behavior of complex and nonlinear systems. However, the inability of traditional neural networks (NNs) to implicitly account for uncertainties has always been a limiting factor. This limitation can be significantly mitigated by using Bayesian Neural Networks (BNNs) instead of traditional NNs. Using BNNs allows parameters to take values from probability distributions optimized during training, thereby incorporating uncertainty in the predicted quantities. However, training of BNNs and even NNs has always been a computationally expensive task requiring a large dataset. For complex systems, high-fidelity data is generally accurate but costly to generate and is often insufficient to train BNNs to predict quantities of interest up to a satisfactory level of accuracy. On the other hand, low-fidelity data, in general, is inexpensive to generate but inaccurate. Transfer learning is a viable approach toward overcoming the large training data requirement by combining the low- and high-fidelity datasets, as it utilizes the knowledge learned from the training of a neural network for a similar problem in training for another related problem. In this study, we compare different transfer learning strategies to train BNNs on a bi-fidelity dataset that combines a larger low- and a smaller high-fidelity dataset to train a BNN for modeling a nonlinear suspension system of a car.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GENERALIZED DEFLATION SCHEMES FOR NONLINEAR, NONSYMMETRIC EIGENVALUE PROBLEMS

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ABSTRACT

Our primary motivation -- and ultimate goal -- is the complete solution of time-dependent problems in the frame of a generalized modal analysis that requires finding a set of eigenpairs of interest of an in principle arbitrary, high-order nonlinear eigenvalue problem. The mathematical modeling of the original mechanical system leads to generalized stiffness, mass, and damping matrices (as in structural engineering) of a frequency-dependent series that must satisfy some linear algebra properties. For large-scale problems, the only feasible way of dealing with the proposed subject is by using just a subset of eigenpairs of interest in the modal analysis. This is very challenging, and the procedure of eigenpair evaluation must include removing -- by deflation -- already found eigenpairs from the search subspace interval. The present contribution is dedicated to deflation algorithms.

After introducing the nonlinear eigenvalue problem in its most general framework and a brief literature survey, we outline a novel mathematical scheme for deflating eigentriples of nonsymmetric, complex, nonlinear problems that may or not have mechanical meaning, thus going far beyond our primary scope. The eigenvalue problem may be considered either in terms of closed-form, exact analytical functions or developed as a power series of the eigenvalues, the latter being an approximation but more efficient to handle computationally. We show that a general deflation scheme ultimately deals with the original problem accrued by a penalty function that prevents already obtained results from being re-evaluated. In our attempt to exhaust the proposed mathematical possibilities, we also present an alternative deflation algorithm that may not preserve the problem's original structure but which works as well if combined with an oblique, weighted biorthogonal projection, which only needs to be resorted to when dealing with nonlinear nonsymmetric problems. We carry out an illustrative, general numerical assessment for evaluations using a modified, inverse-free Krylov subspace iteration scheme for nonlinear symmetric problems generated randomly. The numerical application to more general, complex, nonlinear, nonsymmetric eigenvalue problems is also presented.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PERFORMANCE OPTIMIZATION OF CROSS FLOW TURBINE FOR ENERGY GENERATION FROM MOVING WATER

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ABSTRACT

Given that the continental United States has a theoretical river power resource of 1381 TWh/yr and a technically recoverable resource of 119.9 TWh/yr [1, 2], generating power from riverine, currents or man-made channels can reduce the reliance on fossil fuels for electricity. More importantly, when located near to the point of need, energy generation from moving waters can become an attractive solution for areas where connectivity to a grid is not available or for areas subjected to disruptions caused by natural or accidental events. Towards advancing available technologies for efficient power generation, we focus on the optimization of the performance of a crossflow turbine when placed in moving waters. The need for such turbines to operate over a limited range of water speeds with a relatively high level of turbulence, unsteady effects with potential free surface effects, and the inherently unsteady hydrodynamics associated with the turbine present the need and opportunity for performance optimization of individual rotors or arrays. Our optimization effort will be based on experimentally validated numerical simulations. The experiments were carried out in the towing tank of the Davidson Laboratory at Stevens Institute of Technology. In these experiments, the turbine's rotational speed and generated torque were measured at different towing (or flow) speeds under different electric loads applied by adjusting an electromagnetic break. These measurements were used to generate various characteristic curves for the purpose of validating the high-fidelity hydrodynamic simulations and, consequently, guide the optimization efforts.

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Structural reliability, bridges, and truck loads
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VARIATION IN RELIABILITY OF BRIDGE GIRDERS FLEXURALLY STRENGTHENED WITH EXTERNALLY BONDED FRP

Chris Eamon[1], Safaa Dardar[1] and Gustavo Parra-Montesinos[2]*

[1]*Wayne State University*
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ABSTRACT

The use of externally-bonded fiber-reinforced polymer (FRP) laminates is often an efficient and cost-effective method to strengthen existing reinforced concrete bridge girders, and various guidelines are available to address this issue. However, the reliability of girders strengthened to AASHTO provisions is largely unknown. In this study, the reliability of reinforced concrete bridge beams that are flexurally strengthened with externally bonded carbon fiber-reinforced polymer (CFRP) laminates according to AASHTO design and FRP strengthening provisions was quantified. The flexural resistance model considers resistance loss due to the effect of bar corrosion, FRP strength and stiffness degradation, FRP rupture, and debonding. Random variables were used to characterize uncertainties in as-constructed initial beam geometry and material properties, as well as loads and loss of beam resistance due to steel, concrete, and CFRP system degradation. The bond strength loss model was based on 19 years of actual in situ deterioration data. The effects of various critical parameters on reliability were quantified, including beam span, concrete strength, the modular ratio and unit area of CFRP, the extent of CFRP repair, and the dead/live-load ratio. It was found that a large inconsistency in reliability exists among CFRP-repaired beams designed according to AASHTO provisions, where the reliability of girders with equivalent strength was found to be greatest for members with longer span, higher concrete strength, low CFRP/steel modular ratio, a smaller extent of repair, a greater number of tension bars, a smaller CFRP unit area, and a higher DL/LL ratio. It was further found that the primary cause of variability in reliability was the influence of many of the factors above on FRP debonding probability, which are not directly accounted for in AASHTO guidelines. The results demonstrate the importance of including a well-developed bond strength model in the design process. Recommendations are suggested that can reduce the large variation in reliability level, potentially producing designs with greater consistency in safety level.

Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FRAMEWORK FOR FIREBRAND GENERATION AND FIRE SPOTTING SIMULATION WITHIN WRF-FIRE

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ABSTRACT

The aim of this study is to develop models to simulate firebrand generation and ignition upon landing, and implement the resulting models within a coupled wildland fire-atmosphere simulation platform, known as WRF-Fire, for fire spotting simulation. Fire spotting occurs when firebrands are lofted into unburned areas and ignite new fires. Therefore, fire spotting simulation is an important piece in achieving realistic and skillful wildfire propagation simulations. To develop the generation model, available experimental data in the literature are utilized together with regression techniques to develop a firebrand generation model that relates fuel characteristics, fuel consumption, and wind speed to firebrand yield, mass, and area. The developed model is then validated against other datasets available in the literature not used in the model fitting. For the fire spotting simulation, an ignition model is developed based on the heat released, radiative, and convective heat losses from landed firebrands to the ambient, the energy required to dry unignited fuel bed, and the energy required to heat the fuel bed to ignition temperature. This model primarily utilizes combustion and thermodynamics equations whose parameters are calibrated based on observational data. Next, utilizing the developed generation and ignition models, an MPI-enabled fire spotting simulation framework is implemented within the WRF-Fire simulation platform to simulate firebrand generation, transport, and spot fire ignition. The framework is then evaluated in a landscape-scale historic fire, the 2018 Camp Fire, to explore the effects of fire spotting on the simulated fire progression. The simulation results are validated against high-resolution, semi-continuous fire perimeters as well as spot fire locations estimated from NEXRAD radar reflectivity observations.

High-dimensional data analytics and machine learning in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A B-SPLINES-BASED METHOD FOR SPARSE RECOVERY OF GUIDED WAVES DISPERSION CURVES

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ABSTRACT

This research presents a technique to recover the dispersion curves of guided-waves by utilizing the inherent sparsity of these signals in the frequency-wavenumber domain. The proposed methodology is a data-driven approach that combines physics-based knowledge with high-dimensional analysis to obtain the dispersion curves of the medium from experimental signals. This study utilized experimental data from a guided-wave experiment on an aluminum plate. The signals were converted to the frequency-distance domain with a frequency range limitation of 150 to 750 kHz, as shown in Figure 1. Initially, a sparse two-dimensional dispersion matrix is constructed using sparse wavenumber analysis. Then, B-splines are fitted to non-zero elements of this matrix to establish an initial estimate of the dispersion curve parameters. These parameters are further optimized using the quasi-Newton algorithm to improve the accuracy of signal prediction. The optimized B-spline functions fitted for the wavenumbers of three contributed dispersive modes are presented in Figure 2. The results demonstrate that this method can significantly reduce the dimensions of Lamb waves signals to approximately 0.05%, which avoids overfitting. In order to evaluate how well the conversion maintains the information in the original domain, the correlation between the observed and predicted signals is determined. The results indicate that the proposed method is comparably precise to Sparse Wavenumber Analysis, while utilizing a reduced number of dimensions. In comparison with sparse wavenumber analysis, this technique requires two orders of magnitude fewer parameters to represent the medium's dispersion curves.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A GENERALIZED ANISOTROPIC DAMAGE MODEL FOR BRITTLE ROCKS BASED ON MICROMECHANICS AND THERMODYNAMICS

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ABSTRACT

This work presents a generalized three-dimensional anisotropic continuum damage model for brittle rocks within a thermodynamics framework and based on micromechanics. Damage in rocks is considered to be the direct consequence of microcracks growth. Despite the many studies suggesting a generally anisotropic second-order tensor to be sufficient for describing damage, it is shown here through a micromechanical investigation that damage should indeed be presented in its most general form as an anisotropic fourth-order tensor; otherwise, important characteristics of rock behavior in frequently encountered scenarios including uniaxial and biaxial stress fields cannot be captured accurately. For the developments in this work, a Representative Volume Element (REV) of rock is considered which includes the rock matrix embedding short oblate spheroidal (penny-shaped) microcracks which are open at all times and have arbitrary directional distribution. Following a rigorous up-scaling procedure, an elastic-damage constitutive law is derived for the homogenized behavior of micro-fractured rock at the continuum scale in which the damage is defined as the fourth-order microcrack fabric tensor. By formulating the free energy for the REV which takes into account the interaction between microcracks, a generalized fourth-order thermodynamic force conjugate to the damage is defined. It is shown how this force is linked to the concepts of energy release rate and stress intensity factor in Linear Elastic Fracture Mechanics (LEFM). This linkage facilitates defining a simple damage criterion for rocks based on the thermodynamic damage force reaching a critical value with a hardening behavior. Damage evolution is the only source of dissipation and is described here through a simple law based on the principle of maximum energy dissipation (normality rule). Several examples are provided at the material point level to validate the proposed formulation against classical analytical results in LEFM and show its robustness in capturing salient feature of rocks behavior, including induced anisotropy and preferential failure direction, under general loading conditions.

DYNAMIC BEHAVIOR OF TRANSMISSION LINE SYSTEMS PRONE TO NON-UNIFORM DOWNBURST WIND LOADING

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ABSTRACT

Transmission line systems are susceptible to damage under severe thunderstorm events, including downburst winds. Although the downburst is a localized wind event in a relatively small area compared to other wind hazards, the failure of one tower can adversely influence the adjacent towers and the entire line. That means one event can cause enormous destruction to the whole system. The power network infrastructure plays a significant role in our modern society in which electricity has been integrated into the welfare of our communities. By extension, the resilience of our communities broadly relies on the resilience of transmission line systems (TLSs) against high-intensity wind events (e.g., downbursts and tornadoes). Therefore, the ultimate goal of designing TLSs is to ensure structural safety alongside the sustainability of the tower and the entire system. On the one hand, the preceding efforts have proved that downburst wind loading is relatively larger than the atmospheric boundary layer (ABL) wind loading, considering the uniformity in loading conditions. On the other hand, the influence of non-uniform downburst wind loading on the dynamic behavior of large-scale TLSs, to the authors' knowledge, has not been experimentally investigated— a gap that is addressed herein. Hence, in this study, the assessment of the dynamic behavior of TLSs under non-uniform downburst wind loadings is experimentally investigated. These simulations were conducted at the Wall of Wind (WOW) Experimental Facility (EF), located at Florida International University (FIU). In many wind tunnels, this type of simulation encounters inevitable restrictions due to the limited testing space and/or the difficulty of utilizing an appropriate scaling of the TLSs. However, since the WOW has the capacity to test large-scale models, these restrictions are inapplicable to our study. This work involves a TLS comprising four bays spanning 1300ft (full-scale) and three identical self-supported towers of a height of 196ft. At the far ends of the TLS, two end frames were placed to simply support the three conductors. Each tower carried three conductors, with two conductors bundled on each cross-arm and the third suspended at the mid-point of the top girder. In this case of non-uniform loadings, the unbalanced forces are inevitably pronounced in the conductors, causing additional longitudinal and transverse loads on the adjacent tower. Preliminary results indicate that non-uniform loading significantly influences longitudinal response more than the transverse response on the adjacent tower. This shows the significance of comparing the uniform and non-uniform loading cases under various wind speeds.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE ROLE OF BULK STRENGTH IN GENERATING A SPECTRUM OF FAULT SLIP PATTERNS

Md Shumon Mia[1], *Amr Ibrahim*[2], *Mohamed Abdelmeguid*[3] *and Ahmed Elbanna**[1]

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ABSTRACT

Frictional faults are ubiquitous in the subsurface. They host a wide range of seismic and aseismic phenomena ranging from creep to large earthquakes and including a spectrum of slip patterns such as slow slip, tremors, and repeaters. It is critical to understand the dynamics of these different slip patterns as they impact the structural reliability of the infrastructure and subsurface geo-energy activities. Conditions governing the stability of frictional sliding and resulting patterns are often attributed to the on-fault frictional properties with idealized elastic off-fault materials. However, fault slip leads to the inelastic deformation in the off-fault material which may influence the resulting slip patterns. Here we study the role of off-fault material property namely the yield strength on the long-term slip patterns. We simulate both an elastoplastic spring slider system and 2D continuum model of an anti-plane fault embedded in elastoplastic bulk. We use a rate and state dependent friction law to model the frictional interface and J2 plasticity to capture inelastic response of the off-fault bulk. An in-house hybrid numerical scheme, FEBE, combining FEM and spectral boundary integral enables us to carry out high resolution modeling of the potential elastoplastic fault zone.

Using the spring slider model, we identify a new stability transition from locked fault to unstable stick-slip. Continuum simulations of the rate-and-state fault also shows similar results with different slip patterns including locked fault, slow slip, and spatially localized stick-slip. When the yield strength is sufficiently low and close to the frictional strength, the fault may remain locked or undergoes slow slip even if the fault's frictional properties are favorable for generating unstable sliding. The slip deficit of the locked fault is compensated by the off-fault inelastic deformation. When the yield strength is increased, the coevolution of fault slip and off-fault plasticity gives rise to a complex unstable slip patterns including spatial arrest of ruptures and temporal clustering of event timings. Furthermore, simulations with heterogeneous yield strength show that the mean value of yield strength controls the long-term slip patterns with different time windows for the transition depending on the degree of heterogeneity. These findings shed new light on the understanding of seismic source mechanics and contribute to improving seismic hazard analysis.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LOCALIZATION AND INSTABILITY IN FLUID INFILTRATED SHEARED GRANULAR MATERIALS

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ABSTRACT

Understanding the fundamental mechanisms of deformation and failure in sheared fault gouge is critical for development of physics-based earthquake rupture simulations and next generation seismic hazard models. We use a non-equilibrium thermodynamics model, the Shear Transformation Zone (STZ) theory, to investigate the dynamics of strain localization and its connection to stability of sliding in the presence and absence of pore fluids. STZ theory, first introduced by Falk and Langer in 1998, assumes that plastic deformation in amorphous materials occurs in a few localized regions that are susceptible to non-affine particle rearrangements. These localized regions are called shear transformation zones (STZ). Inside STZs the particles can move and rearrange their configuration. Each of these rearrangements generate local plastic strain. The density of STZs is governed by a state variable called effective temperature (or compactivity). There is a one-to-one correspondence between compactivity and porosity. The steady state value of compactivity is rate dependent. We extended the STZ formulation to account for pore pressure diffusion and temperature evolution both phenomena which may be affected by shear heating associated with slip.

We investigate the conditions leading to localization of deformation and emergence of stick-slip instabilities. During athermal strain localization, i.e. in the absence of feedback between shear heating and temperature or pore pressure variation, gouge dilates and the pore pressure decreases. With thermal pressurization, where the rise in temperature leads to an increase in pore pressure, strain localizes to an extremely thin shear band, the shear strength drops almost to zero, and the temperature within the shear band increases rapidly to levels that may cause global melting. Stability transitions and the degree of strain localization depends on the competition between dilation and shear heating. We discuss the implications of these findings on strength evolution and flow properties of fault gouge highlighting additional physical mechanisms that may be needed to fully understand energy partitioning in earthquakes.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VALIDATION OF SYSTEM-LEVEL ASSUMPTIONS IN SEISMIC ANALYSIS OF RC STRUCTURES: AN EXPERIMENTAL FRAMEWORK BASED ON 3D PRINTING OF THE REINFORCEMENT

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ABSTRACT

Additive manufacturing is considered a revolutionary technology with many applications in Civil Engineering. This paper discusses a recently proposed new application that is based on using additively manufactured steel reinforcement cages for manufacturing small-scale (on the order of 1:30-1:40 scale factors) physical models of Reinforced Concrete (RC) structures, since it is inefficient to manufacture such reinforcing cages by hand. Such a manufacturing process makes the construction of multiple specimens more efficient and timewise feasible – something that was not possible before 3D printing. The aim of this framework is to validate the global-level assumptions of numerical models of RC whole structures (e.g., damping formulation, interaction of components). Such validation should take place for given component-level behavior, experimentally obtained via cyclic tests performed at the model scale. To preserve similitude of stresses, the system-level tests are to be performed on a shake table mounted in a geotechnical centrifuge. The proposed framework allows for increasing the available datasets for model calibration.

This paper discusses material and component-level tests performed at the model scale (Elmorsy et al. 2023a, 2023b). The tests reveal that (a) the mechanical properties of 3D printed submillimeter rebars can be adjusted by modulating the printing parameters, (b) reasonable (compared to full scale rebars) bond behavior between the rebars and the concrete can be achieved by adjusting the mix design and the rebar surface ribs, and (c) upon testing RC columns and beam-column subassemblies under cyclic loading, similar (to full-scale) failure mode, stiffness, strength, and ductility could be achieved.

Elmorsy, M., Wrobel, R., Leinenbach, C., & Vassiliou, M.F. 2023: Material Testing of Micro-Concrete and 3D-Printed Reinforcement for Use in Small-Scale Seismic Testing of RC Structures, 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN), Athens, Greece.
Elmorsy, M., Wrobel, R., Leinenbach, C., & Vassiliou, M.F. 2023: Additively Manufactured Steel Reinforcement for Small Scale Reinforced Concrete Modeling: Tensile and Bond Behavior, Materials and Design (under review).

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROPAGATION OF RC BEAM-COLUMN JOINT MODELING UNCERTAINTY TO THE SEISMIC PERFORMANCE OF RC BUILDINGS USING INCREMENTAL RECORD-WISE LHS

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ABSTRACT

Beam-column joints are critical elements for the structural integrity of Reinforced Concrete (RC) framed buildings under earthquake loading. Many aspects of joint modeling can have a significant impact on the estimate of collapse performance, while non-negligible parameter uncertainties are present in their strength, stiffness, deformation capacity, and cyclic deterioration. An accurate test-informed probabilistic beam-column joint model is of paramount importance as it can improve cost and time efficiency of new building designs and retrofit measures of existing buildings. Based on a recently collected cyclic-test database on 771 RC beam-column joints, probabilistic joint macro models have been proposed (Elmorsy 2020). Models were proposed for both ductile RC joints and seismically deficient (shear deficient) RC joints, without shear reinforcement, which is typical in existing buildings in the US that were built prior to the 1980s.

On this basis, incremental record-wise Latin Hypercube Sampling (iLHS) (Vamvatsikos 2014; Kazantzi et al. 2014) accompanied by Multiple Stripe Analysis (MSA) is applied to quantify the resulting seismic performance uncertainty due to joint modeling uncertainty. Two frames are used as case studies; one designed according to modern codes (new) and the other is deliberately designed to contain joint shear deficiency (existing). Structural collapse risk sensitivity due to the RC beam-column joint modeling uncertainty is assessed for both new and existing (with joint shear deficiency) frames, quantifying its effect on structural performance.

Elmorsy, M., 2020. Nonlinear modeling parameters for beam-column joints in seismic analysis of concrete buildings (Master Thesis, University of Alaska Anchorage).
Vamvatsikos, D., 2014. Seismic performance uncertainty estimation via IDA with progressive accelerogram-wise latin hypercube sampling. Journal of Structural Engineering, 140(8), p.A4014015.
Kazantzi, A.K., Vamvatsikos, D. and Lignos, D.G., 2014. Seismic performance of a steel moment-resisting frame subject to strength and ductility uncertainty. Engineering Structures, 78, pp.69-77.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NOWCASTING THUNDERSTORM WIND SPEEDS BY INTEGRATING MULTI-SOURCE DATASETS TO ENHANCE SAFETY OF SOLAR TRACKERS

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[2]University at Buffalo

ABSTRACT

Nowcasting wind speed is a vital technique with broad applications ranging from air traffic management to energy production optimization. For solar farms, wind speed nowcasting helps solar trackers proactively respond to the sudden increase in wind speed to minimize the structural damage. Specifically, wind speed nowcasting allows for protective measures such as quickly moving solar panels into the stow position to reduce risks of wind damage. Although existing literature discussed nowcasting wind speeds, they have been limited to predicting stationary synoptic wind events. Thunderstorms can produce short-lived extreme wind events with speeds exceeding 100 mph. Nowcasting such a sudden increase in high wind speeds has been a challenging problem due to the nature of strong non-stationarity and the limited available data for such localized events. To address this challenge, a machine learning model that utilizes multi-source datasets is developed. Specifically, a long short-term memory-based neural network is first constructed. Then, this machine learning model is trained with multi-source data from Automated Surface Observing System (ASOS) stations, Radar, Satellite, and NWP models. To ensure that the model is versatile and reliable, it is trained on diverse datasets from various locations across the US. The results show that the model is capable of providing promising accuracy in nowcasting extreme wind speed with a lead time of 5-10 minutes. This lead time is adequate for most solar trackers to transition into the stow position, thereby enhancing structural safety.

A COMPARATIVE STUDY OF WOOD-PLASTIC COMPOSITE INFUSED STRUCTURAL INSULATED PANELS AND REINFORCED CONCRETE FOR SUSTAINABLE CONSTRUCTION

Mohamed Elnakeb[1], Marina Moawad[1], Mohamed Ashmawy[1], Marwan Shawki[1], Mohamed Atef[1], Ehab Abdelhamid[1], Mohamed Darwish[1], May Haggag[1], Donia Eldwib[1], Khaled Nassar[1], Maram Saudy[1], Safwan Khedr[1], Minas Guirguis[1], Elkhayam Dorra[1] and Mohamed Abouzeid[1]*

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ABSTRACT

The global construction industry's profound impact on carbon emissions and its contribution to global warming necessitates an urgent exploration of innovative building solutions. These impacts are particularly pronounced in regions facing multiple challenges such as waste disposal issues, widespread poverty, and adequate housing issues. This work undertakes a multi-disciplinary approach to address such challenges, focusing on the adoption of Structural Insulated Panels (SIPs) as an unconventional structural system. Notably, the work integrates waste materials into SIPs composition using Wood-Plastic Composite (WPC), made from recycled Sengon wood sawdust and HDPE , for facings. The primary objective of this work is to assess the feasibility of designing a 5-story Mid-Rise structure utilizing WPC SIPs. The research commences by developing an interaction diagram for SIPs, through which the maximum unsupported span could be determined using the SIP depth and the design working load. This interaction diagram is developed for SIP sections with and without stiffeners. The results show that SIPs with stiffeners can reach 4.5 times more unsupported span length compared to the ones with no stiffeners. Furthermore, it is found that the structural design is mainly governed by the deflection limitation design criterion. The findings affirm that designing a structurally safe and sound Mid-Rise structure from SIPs is attainable within the defined structural capabilities. Comparative analyses with a conventional Reinforced Concrete (RC) structure are conducted across multiple dimensions, including carbon emissions, construction cost, thermal conductance, energy consumption, Life-Cycle-Cost, and Life-Cycle-Carbon-Emissions. The results highlight the significant advantages of the WPC SIPs structure, including a 90% reduction in carbon emissions, while having a 5.3% higher construction cost compared to the RC structure. However, the SIPs structure has 95% lower thermal conductance, 80% less energy consumption, 53% reduction in Life-Cycle-Cost, and 82% reduction in Life-Cycle-Carbon Emissions over a 40-year period. This study contributes valuable insights into sustainable construction and the proposed WPC SIPs system emerges as a promising alternative with tangible environmental and economic benefits.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF EXCESSIVE CLAMPING FORCE ON BOLTED CFRP COMPOSITE PLATES

Alaa Elsisi[1] and Hani Salim[2]*

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[2]University of Missouri

ABSTRACT

The friction-type bolted joints are widely used in both the civil and aerospace industries. Uncontrolled excessive bolt clamping force can crush the laminated fiber-reinforced-polymeric (FRP) composite through the thickness and damage the joint before applying the service loads. The effect of the friction coefficient, bolt clearance, joint type, and other parameters on failure modes and the maximum bolt clamping force of the carbon FRP lapped joint is studied. A three-dimensional finite element (FE) model consisting of a bolt, a washer, a laminate FRP composite plate, and steel plates was developed for the simulation of the double (3DD) and single (3DS) lapped bolted joint. The FE model was validated by using experimental results. The joint capacity of the clamping force was found to be greatly increased by adopting the double lap technique, which involves placing an FRP composite plate between two steel plates. Also, it was recommended to use an internal washer diameter less than or equal to the FRP composite plate hole diameter since a larger washer clearance can produce higher contact pressure. In addition, reducing the bolt head diameter can lead to a 65% reduction in the 3DS joint clamping strength.

EFFICIENT BEAM ELEMENT MODEL FOR ANALYSIS OF SANDWICH BEAMS WITH PARTIAL SHEAR CONNECTIVITY

Alaa Elsisi[1] and Hani Salim[2]*

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[2]University of Missouri

ABSTRACT

A two-node beam element with eight degrees of freedom was developed and implemented into MATLAB to simulate the nonlinear behavior of the reinforced concrete sandwich beams. The beam element includes the concrete layers, the reinforcement, and the tie connectors. One dimension-softening model was used to simulate the concrete, the bilinear isotropic plastic model was used to simulate the steel, and a multi-linear spring was used to simulate the partial shear connectivity. Experimental results were used to validate the numerical model, which was able to closely predict the experimental response by a 2% difference. The model was able to simulate several material nonlinearities such as the plasticity of the steel rebar and cracking and crushing of concrete.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING THE VISUAL STRUCTURAL INSPECTIONS USING AI-ASSISTED CRACK DETECTION TOOLS

Kareem Eltouny[1], Shivani Gandage[1] and Nicholas Catella[1]*

[1]Simpson Gumpertz & Heger

ABSTRACT

The onset of the big data revolution has opened countless possibilities for efficiency in visual inspection and condition assessment. At Simpson, Gumpertz & Heger (SGH), we initiated an experimental project to enhance the structural investigations process by leveraging the latest improvements in deep learning and computer vision. In this study, we present the first iteration of the SGH Crack Detection Tool (CDT) that can efficiently identify and map cracks based on visual data. To validate the tool's prediction performance, we tested CDT on crack detection benchmarks, achieving state-of-the-art results. The AI-powered tool can provide crack segmentation masks of a variety of sizes relying on various inference techniques that allow for ultra-high-resolution predictions. The development also focused on usability and accessibility, incorporating an intuitive graphical user interface, to offer inspectors a user-friendly experience. In addition to sample results, the presentation will include live demonstrations to showcase the tool's prediction capabilities. Furthermore, the challenges faced during the development of CDT will be discussed. CDT is an important component of the SGH AI-assisted toolsets designed to aid engineers in making faster and more accurate decisions in a human-AI collaborative environment.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING ANISOTROPIC MECHANICAL PROPERTIES OF CORNEA AND THE EFFECT OF CXL THERAPY

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ABSTRACT

This research was aimed at using the biaxial testing method in order to assess corneal biomechanical properties and resolve the persistent uncertainty among researchers regarding its anisotropic mechanical response. The primary objective was to elucidate new insight into the mechanical response of the cornea before and after corneal crosslinking (CXL) treatment through performing biaxial testing on porcine corneas. Fresh porcine eyeballs were acquired from a local slaughterhouse and brought to the laboratory on ice. At the laboratory, the excess tissues, epithelial layer, and endothelial layer were meticulously removed, and corneal rings, each encompassing approximately 2 mm of sclera, were excised from each eyeball. The original CXL procedure, commonly known as the Dresden protocol, was used to create crosslinks in the samples. This surgical procedure utilizes drops of riboflavin and 20% dextran solution and projects UVA light, with a wavelength of 370 nm and intensity of 3 mW/cm2, onto the cornea. Both control and crosslinked samples were sectioned as squared strips, and their thickness was measured by a pachymeter. The samples were soaked in a PBS solution to bring their average thickness to 700 microns before mounting them into the biaxial testing machine; this was done in order to minimize variation in the measurements because of hydration effects. The biaxial tests were conducted by employing bio-rake grips and moisture-preserving handling of corneal strips, i.e., a PBS spray was used to keep samples moist and to prevent any significant changes to their hydration throughout the experiments. The displacement control tests with various stretch ratios and displacement rates were conducted after subjecting the samples to loading-unloading preconditioning cycles. The stress-strain curves, obtained under different loading conditions, showed a steep increase in the stress with increasing applied strain in both superior-inferior (SI) and nasal-temporal (NT) directions, the testing axes of the biaxial device. Furthermore, in agreement with what was previously reported using uniaxial tensile testing studies, the biaxial measurements showed that the CXL treatment significantly stiffened the tensile properties of the cornea. However, the findings indicated the absence of any directional anisotropy. Overall, larger tensile moduli were found using the biaxial testing method compared to the uniaxial testing technique. In summary, this study examined corneal mechanical properties by performing planar biaxial tests, revealing an almost isotropic mechanical behavior along the NT and SI directions. These findings offer valuable insight into corneal biomechanics, particularly regarding its response after the CXL treatment.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PAVEMENT SUBSURFACE MONITORING WITH EMBEDDED WIRELESS PASSIVE RF SENSING SYSTEM

Kent Eng[1], Zygmunt Haas[2], Petar Djuric[3], Samir Das[3], Milutin Stanacevic[3] and Branko Glisic[1]*

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ABSTRACT

Roads are a critical infrastructure in modern transportation systems. Existing monitoring technology primarily focuses on the surface course rather than the subsurface courses. Factors such as aging, overuse, water infiltration, land sliding, and climate change in general, can deteriorate the subsurface course performance which ultimately leads to pavement distress and even structural failure. The subsurface courses, including base, subbase, and subgrade provide road stability and load-bearing capacity throughout the service period. The current subsurface monitoring systems are either wired or battery-required, which is a challenge in large-scale implementation. Therefore, it is of interest to develop a wireless and battery-less subsurface course monitoring system to effectively implement on a large scale for assessing and maintaining the road conditions.

This presentation aims to present novel embeddable passive radio frequency (RF) sensing systems and demonstrate the proof of concepts on its applicability in subsurface course monitoring. By leveraging backscatter techniques and wireless channel information, these sensors can measure the distance relative to each other which can potentially represent the change in subsurface course condition or performance. Controlled experiments are conducted in the laboratory to examine the system performance under various simulated load scenarios. The main challenge of this research includes replicating subsurface conditions in the laboratory setting and identifying the changes in subsurface materials that affect the sensed RF channel information.

The results show that the embedded wireless passive RF sensing system captures the changes in the replicated subsurface course conditions. This successfully demonstrates proof of concept on sensor applicability in subsurface course health monitoring. By further resolving the implementation challenges, the system can potentially be deployed in real-world scenarios.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYSIS OF FRACTIONAL DYNAMICAL SYSTEMS USING RECURSIVE BAYESIAN ESTIMATION METHODS AND RESPONSE DATA

Kalil Erazo[1], Alberto Di Matteo[2] and Pol Spanos[1]*

[1]Rice University
[2]University of Palermo

ABSTRACT

Recursive estimation methods integrate analytical models with noisy vibration data to infer the parameters and response of dynamical systems. The objective is to optimize the predicting capability of a model by minimizing (in some sense) modeling uncertainty and modeling errors. The inferred response and parameters are applied to structural condition/damage assessment and prediction, improvement of design methods, and structural control. In this work the application of a class of time-domain recursive inverse methods in the context of structural systems comprising fractional derivative elements is studied. In contrast to classical linear systems, where stiffness and damping are independent structural characteristics, fractional-order elements influence both stiffness and damping simultaneously which allows to model the response and behavior of dynamical systems exhibiting strong memory characteristics more accurately. Engineering applications of systems exhibiting strong memory characteristics include damping and energy dissipation mechanisms, fluids sloshing, creep and relaxation, among others. The recursive estimation methods studied use vibration data, typically in the form of noisy acceleration measurements, and combine the data with a numerical model of the system of interest in a probabilistic setting. The use of response measurements allows solving the inverse problem of parameter estimation, response estimation, and/or input estimation, and reduces inherent modeling errors that result from the analytical and numerical models employed.

The effectiveness of recursive nonlinear filtering-based parameter estimation methods in the identification of structural fractional systems is assessed. The study includes results for multiple degrees-of-freedom systems and nonlinear-hysteretic systems. Further, an experimental analysis is conducted to assess the effectiveness of the methods using real data. The experimental system consists of a frame structure equipped with a tuned liquid column damper device applied for vibration suppression/control. The system exhibits fractional calculus features due to fluid sloshing in the device. The use of a traditional nonlinear sloshing model, as well as of a fractional model, is explored.

The advantages and limitations of the proposed framework are examined using pertinent numerical simulations and the experimental data. The analyses are performed under several conditions, including various measurement noise levels, known and uncertain inputs (input-output and output-only implementations), different kinds of inputs, and various kinds of measurements.

A MODEL-BASED FRAMEWORK FOR STRUCTURAL DAMAGE ASSESSMENT OF INSTRUMENTED CIVIL INFRASTRUCTURE SYSTEMS

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ABSTRACT

The reliable diagnosis and prognosis of structural damage in civil infrastructure systems is the main goal of structural health monitoring (SHM). The objective is to use response measurements (typically dynamic response parameters) to infer the state of structural integrity before and/or after severe events, and to predict the future structural performance or remaining useful life. SHM approaches can be broadly classified as data-driven and model-based. Data-driven approaches rely solely on the data, while model-based approaches incorporate a mechanics-based structural model in the analysis.

In this work a model-based approach for structural damage assessment of instrumented civil infrastructure systems is presented. The approach integrates a physics-based structural model, a mechanics-based damage model, and vibration response measurements to estimate the state of structural integrity before and/or after severe events. Instead of relying in stiffness-based characteristics (which are difficult to correlate to the specific type of physical damage and its severity), the approach employs experimentally calibrated damage models to locate and quantify structural damage. This chiefly allows to estimate a quantitative measure of damage that can be mapped through model calibration in order to assess the type and severity of damage. The proposed approach is validated using numerical and experimental examples.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVERSE IMPORTANCE SAMPLING-BASED FRAMEWORK FOR RELIABILITY ESTIMATION IN COMPLEX, HIGH-DIMENSIONAL SPACES

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ABSTRACT

This work advances our Approximate Sampling Target with Post-processing Adjustment (ASTPA) framework, a computationally efficient approach for reliability estimation, recently developed in [1], where it demonstrated exceptional performance for Gaussian spaces. In essence, the failure probability estimation is a normalizing constant estimation problem for the joint distribution of the involved random variables truncated over the failure domain, also known as the optimal sampling target, a demanding problem traditionally approached through sequential techniques. Conversely, ASTPA innovatively and uniquely addresses this challenge by alternatively estimating the normalizing constant of an approximate sampling distribution, relaxing the optimal one. That significantly reduces the original problem's complexity and results in unprecedently efficient reliability estimates in challenging scenarios. The sampling target in ASTPA is constructed utilizing a cumulative distribution function and the limit state function, placing greater importance on the failure domains. Post-sampling, its normalizing constant is accurately estimated using our devised, original inverse importance sampling (IIS) procedure, that utilizes an importance sampling density properly suggested based on the already acquired samples. In this work, we first enhance our Hamiltonian MCMC-based ASTPA for directly working in complex non-Gaussian spaces, particularly beneficial when Gaussian implementation is not possible. To this end, our Quasi-Newton mass preconditioned HMCMC (QNp-HMCMC), mainly aiming to adapt to the structure and topology of the target distribution, is further advanced through efficient, automatic initialization and tuning techniques, allowing ASTPA to adeptly work in extremely challenging non-Gaussian domains. In cases when gradients are not available, a substantial development is also shown here through a novel gradient-free sampling technique, currently tailored for Gaussian spaces. This technique starts with a discovery stage for the failure domain, statistically designed to provide (multi-modal) failure samples, subsequently utilized as initial seeds for chains of a gradient-free sampler. We then resort to the dimension-robust preconditioned Crank-Nicolson (pCN) algorithm to sample the approximate sampling target in ASTPA. The proposed initialization approach not only boosts the sampling efficiency of the pCN algorithm in the context of reliability estimation but also extends its applicability to multi-modal cases. A series of diverse problems involving high dimensionality, multimodality, and significant nonlinearity is finally presented, showcasing the capabilities and efficiency of the suggested framework, and demonstrating its superiority compared to the state-of-the-art Subset Simulation and advanced importance sampling-based methods.

Reference:
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Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENT-INFORMED FINITE-STRAIN INVERSE DESIGN OF SPINODAL METAMATERIALS

Michael Espinal[1], Prakash Thakolkaran[2], Siddhant Kumar[2], Somayajulu Dhulipala[1] and Carlos Portela[1]*

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[2]Delft University of Technology

ABSTRACT

Advances in additive manufacturing have unlocked new capabilities to engineer mechanical metamaterials with properties previously unattainable using conventional techniques. Inspired by self-assembly processes, spinodal metamaterials have gained scientific interest for their extreme mechanical resilience and mitigation of stress concentrations, owing to their aperiodic and smoothly curved bicontinuous morphologies. Deriving these morphologies through phase-field modeling or employing a statistical approximation through a Gaussian random field (GRF) method has allowed the fabrication and testing of a multitude of tailored morphologies across a vast anisotropic design space. Leveraging the computational simplicity of the GRF framework has accelerated the design, fabrication, and characterization of spinodal morphologies. However, characterization of the entire parameter space proves challenging, especially from both computational and experimental standpoints. New machine learning (ML) techniques have been proposed to inversely design spinodal metamaterials for elastic properties, but a mechanistic understanding of their structure-to-property relationship remains unclear. Furthermore, the data sets used for these ML frameworks rely on primarily computational data, within a small-deformation regime.

In this work, we leveraged high-throughput microscale experimentation to generate a ground-truth data set for the inverse design of spinodal morphologies under large, nonlinear deformation. Using two-photon lithography, we fabricated >300 samples of thick-shell spinodal metamaterials (average sample dimensions of 92×92×92 μm), across 107 unique morphologies, derived through the Fourier space representation of the GRF through a spectral density function. The resulting data set of nonlinear stress-strain responses up to 40% strain was complemented with a selection of in situ nanomechanical compressions that allowed mechanistic insight on the nonlinear and irreversible deformation mechanisms, i.e., buckling and self-contact. To further explain the resulting stress-strain responses and better link the spinodal morphologies to their large-deformation behavior, we developed an explicit finite element model that complements our experimental data set. Our model establishes a relationship between spinodal curvature distributions and the observed large deformation mechanisms. This work enhances the mechanistic understanding of spinodal metamaterials, that will enable the development of better physics-based ML models to accurately predict spinodal metamaterials for large deformation applications despite relatively limited datasets. The novel morphologies predicted by these models can potentially be used for targeted energy absorption applications relevant to the medical, transportation, and aerospace industries.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING FOR FORCE FIELD PARAMETERIZATION - APPLICATION TO FRACTURE OF 2D MATERIALS

Horacio Espinosa[1], Yue Zhang[1], Kui Lin[1] and Hoang Nguyen[1]*

[1]Northwestern University

ABSTRACT

2D materials are being employed in the development of next-generation electronics, optical, and sensor technologies, as well as in energy production and storage techniques, e.g., supercapacitors, solar cells, and battery electrodes. Such applications involve frequent mechanical deformations such as stretching and bending, so the materials' lifespan (integrity and reliability) is a critical feature. In this context, the abrupt and brittle failure of 2D materials requires particular attention. In this presentation, I will discuss strategies for the parameterization of interatomic potentials (force fields) for accurately describing crack tips' atomic lattice reconstructions and bond dissociation. The force field predictive capabilities will be determined by comparison to in-situ atomistic fracture experiments. The parameterization of force fields is based on a multi-objective genetic algorithm and machine-learning-inspired protocols, with training and screening data sets involving both equilibrium and far-from-equilibrium pathways such as phase transitions, vacancy formation energies, and bond dissociation energy landscapes. Using monolayer MoSe2 as a testbed, I will illustrate the effectiveness of the combined experimental-computational approach in measuring and predicting the toughness of the material, demonstrating in the process the advantages of ML-inspired force field parameterization in developing computational approaches with predictive capabilities.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS OF METAMATERIALS ENGINEERED WITH DNA

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ABSTRACT

Lattice-based constructs, often made by additive manufacturing methods, are attractive for many applications since they can lead to structures that are light weight and exceptionally strong. Typically, such constructs are made from microscale or larger structural elements, however, smaller nanoscale components can lead to even more unusual properties, including greater strength, lighter weight, and unprecedented resiliencies. Here, colloidal crystals engineered with DNA and solid and hollow particle building blocks (nanoframes and nanocages; frame size: ~ 15 nm) respectively were prepared, and their mechanical strengths were studied. Importantly, these three lattices, which have identical crystal symmetries, exhibit markedly different specific stiffnesses and strengths. Surprisingly, the lattice made from nanoframes is approximately 5x stronger than the lattices made from nanosolids and nanocages, respectively. Nanomechanical experiments, electron microscopy, and finite element analysis show that this property is a consequence of the buckling, densification, and size-dependent strain hardening that define the nanoframe lattices. Finally, these unusual open architectures show for the first time that lattices with structural elements as small as 15 nm can retain a high degree of strength, and as such, they represent target components for making and exploring a variety of miniaturized devices, including 3D microelectromechanical systems, microbattery electrodes, and microrobots.

FORENSIC TECHNIQUE FOR STRUCTURAL MATERIAL IDENTIFICATION OF REINFORCED CONCRETE STRUCTURES USING 2D DIC AND METAHEURISTIC OPTIMIZATION

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ABSTRACT

Identification of the material and structural properties of reinforced cement concrete systems is a very challenging but crucial part of the strength analysis and condition assessment. However, the heterogeneous nature of concrete makes it complex to determine the accurate mechanical properties. A combination of finite element model updating (FEMU) with optimization algorithms and reverse engineering has emerged as one approach for determining the mechanical properties of the materials. However, full-field deformation data is crucial for the FEMU-based reverse engineering methods for property identification. To this end, Digital Image Correlation (DIC) has brought a revolution in the field of experimental data extraction. Leveraging only a few images (in deformed and unreformed states), the displacement and strain fields are obtained without any in-contact physical sensors. In such, the advanced DIC software and image processing algorithms are the key parameters to obtain the mechanical behavior as well as properties of different materials. Thus, this research investigates the material and structural property identification of reinforced concrete beams using the FEM updating via metaheuristic particle swarm optimization and full-field data extraction techniques. Additionally, a nonlinear damage plasticity model is utilized for the numerical analysis to accurately represent the true behavior of concrete. The proposed methodology successfully determined Young's modulus and compressive strength of concrete with negligible error. Furthermore, the yield strength, elastic modulus, and cross-sectional area of steel are also identified. Additionally, both single-variable and multiple-variable optimizations are also performed to identify the reinforced concrete properties separately as well as simultaneously. Performance evaluation of the framework in terms of sensitivity and robustness is also performed. Afterwards, the PSO-based framework is compared with the Hybrid PSO and Genetic Algorithms. The non-linear property (compressive strength) was predicted with an error as low as 0.037%. The outcomes of the study show that the mentioned computational forensics framework using full-field data extraction techniques and optimization algorithms is reliable in material/ structural property identification for structural health monitoring (SHM) purposes. Hence, this research is a revolutionary step in the SHM field and construction industry. Future studies considering more complex RCC structures will be the focus of the authors. Real-field testing of RCC beams with both main reinforcement and stirrups will also be explored.

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UNSUPERVISED DISENTANGLEMENT AND DIMENSION REDUCTION FOR LARGE-SCALE ENGINEERING SYSTEMS

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[3]*Pasteur Labs*
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ABSTRACT

Numerous scientific and engineering systems are inherently high-dimensional and multi-modal. We present GM-VAE, an unsupervised generative learning method that provides dimension reduction and clustering of complex, high-dimensional scientific data. The GM-VAE model comprises a variational autoencoder with a Gaussian mixture model in the latent space. During training, the model learns an evolving low-dimensional latent manifold of the data, facilitating disentanglement into clusters and yielding optimal dimension reduction and clustering. We propose a training strategy that combines the expectation maximization (EM) algorithm and gradient descent for improved accuracy. Through experiments with large-scale datasets from turbulent combustion systems, representations learned by the GM-VAE model provide a physically interpretable dimension reduction, enabling a better understanding of the high-volume, high-dimensional data from various sources. In addition, the GM-VAE framework facilitates comparisons between different physical mechanisms, modeling fidelities, and experiments against simulations.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ISO-COST-REGION ENRICHMENT STRATEGY FOR COST-FREE RELIABILITY-BASED DESIGN OPTIMIZATION

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ABSTRACT

Optimizing complex engineering systems is crucial in challenging industrial environments, where structural requirements must meet several specifications, including performance, cost, and safety. Constrained optimization frameworks adeptly handle engineering requisites by explicitly incorporating uncertainties into constraints, allowing for an exhaustive capture of the random parameters variability. However, this procedure is often time-consuming, involving numerous calls to non-explicit mechanical models, especially when dealing with rare event probabilities. The ongoing challenge is to minimize failure probability assessments to reduce the computational burden and enhance performance.

This work aims at leveraging the efficiency of metamodel-assisted RBDO for computationally inexpensive cost functions. We propose a novel strategy based on iso-cost regions. The iso-cost concept introduced in the RBDO framework allows for confining the search to a subset of the original design space with activated cost levels. This subset helps refine the accuracy of the surrogate model locally, limiting enrichments only in relevant areas close to the optimal cost. This reduces unnecessary metamodel enrichments in high-cost zones, streamlining optimization. Such an approach is inherent in the cost function minimization problem and offers simultaneous exploration of multiple local minima regions. Specifically, the proposed method employs an evolutionary algorithm for seeking the global optimal solution. Global Kriging surrogate models, trained with a sequentially enriched set of evaluations, approximate limit state functions (LSFs) to classify design solution feasibility. The evolution starts with random design individuals, serving both in optimization and in the initial Design of Experiments (DoE). A set of iso-cost levels is properly selected delineating a subset of the original design space. Each iteration constructs a new design candidate generation. The initial DoE is locally updated if necessary by selecting points from the iso-cost levels according to a chosen learning function. The enrichments occur concurrently with optimization. If no feasible solutions exist within the iso-cost levels, the algorithm adapts them accordingly, allowing exploration of new regions. The procedure iterates until the stopping conditions for reliability and solution optimality are met. This method notably enhances local metamodel refinement in cost-effective regions. This evidence is supported by a showcase of the algorithm's performance for different engineering benchmarks.

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Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INSTABILITY ANALYSIS OF PARTIALLY SATURATED GEOMATERIALS FROM DEM-DERIVED HYDROMECHANICAL CONSTITUTIVE TENSOR AND SECOND-ORDER WORK

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[3]*Carleton University*

ABSTRACT

The current research employs a micromechanical approach to characterize the hydromechanical behavior of partially saturated geomaterials within the pendular saturation regime. Using Discrete Element Method (DEM) modeling, this study focuses on elucidating the hydromechanical constitutive relationship and instability of densely packed granular materials under triphasic (solid, water, and air) conditions involving isolated liquid bridges.

Within the elastoplasticity framework, a new numerical scheme is proposed to derive a general hydromechanical constitutive tensor (tangent operator) considering the appropriate stress and strain conjugates. The incremental tangent operator is numerically reconstructed through a complete multi-directional DEM probing at various reference material states. The computed constitutive tensor can be integrated into a bifurcation analysis by evaluating its spectral characteristics.

The second-order work instability criterion is evaluated through DEM simulations by applying perturbations near the stress limit state of a deviatoric loading path. In a partially saturated state, defining the second-order work instability criterion is involved due to the interplay between stress and strain variables, influenced by coupled hydromechanical effects [1]. The multiphysics and multiphasic interactions arising from the capillary effect at the microscale result in intricate macroscale behaviors under triphasic conditions. In this regard, the external and internal second-order works are evaluated using DEM to capture the instability with respect to stress-strain variables in wet conditions. Consistent with the spectral analysis of the computed constitutive tensor, and the vanishing of its mechanical part, the second-order work results support the ‘effective’ role of contact stress in describing failure in wet granular materials.

Finally, a mesoscale analysis is presented to detect shear band localization and validate the well-known Rice criterion [2] within a micromechanical framework. The DEM sample is divided into mesoscale cells, each regarded as a representative elementary volume, allowing the correlation of mesoscale stress and strain through a constitutive law. The presented methodology, which incorporates the use of the tangent operator in the acoustic tensor, interestingly reveals that Rice’s localization criterion reasonably detects the orientation of shear bands when applied to the mechanical part of the hydromechanical tangent operator.

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Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IDENTIFYING HYSTERETIC MODELS FOR BASE-ISOLATION SYSTEMS USING BAYESIAN APPROACHES

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ABSTRACT

Hysteresis is an intrinsic phenomenon prevalent in many nonlinear dynamical systems, such as base-isolators and seismic protective systems, that typically presents complex behavioral characteristics. Numerous models have been proposed to accurately describe the hysteresis observed in these damping systems, including bilinear stiffness models and the family of Bouc-Wen models. These models utilize different formulations of mathematical equations to represent and elucidate the observed behavior. Crucially, the selection of the most appropriate model for a given phenomenon becomes an important task given the many possible formulations. Within this context, Bayesian model selection has emerged as a robust probabilistic approach because it facilitates the evaluation of various models and ultimately identifies the most fitting mathematical representation from a potential set through the application of Bayes' theorem.

This study presents the results of a Bayesian model selection analysis for hysteretic models of base-isolators. A series of tests were conducted on a full-scale, four-story, base-isolated structure at the E-Defense Hyogo Earthquake Engineering Research Center of the National Research Institute for Earth Science and Disaster Resilience (NIED) in Japan. The base-isolation layer of this structure featured several different energy dissipation devices, including two pairs of U-shaped steel dampers, where each pair consists of two orthogonally oriented dampers. Bayesian model selection is performed on the experimental force-displacement data from the steel damper pairs via an advanced nested sampling algorithm, MultiNest, to determine the model most capable of describing the observed damper behavior over the full suite of tests. The uncertainty of the model parameters conditioned on the experimental data is also explored through a hierarchical Bayesian approach that attempts to account for the full suite of experimental tests. Results from the applications of the various Bayesian techniques will be presented along with a discussion of the implications for future surrogate modeling efforts.

Novel Methods in Engineering Mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCED MECHANICAL ANALYSIS AND PROTECTIVE DESIGN FOR ENHANCED SAFETY AND PERFORMANCE OF ELECTRIC VEHICLE BATTERIES

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[1]FAMU-FSU

ABSTRACT

The rapidly increasing electric vehicle (EV) industry demands rigorous safety and performance standards for lithium-ion batteries, particularly under mechanical stress conditions. This study presented a comprehensive analysis of the mechanical behavior of 18650 Li-ion batteries subjected to indentation and compression, complemented by the development and validation of an innovative battery protection system. Leveraging finite element methods, the research simulated the response of 18650 Li-ion batteries under mechanical abuse, based on the experimental tests on the batteries. The study used LS-Dyna software to accurately model the complex structures of the battery, including the jellyroll and shell casing. The simulations extended to replicating the battery behavior under dynamic loading, providing a robust platform for assessing battery safety under mechanical stress. Central to the research was the conceptualization and empirical validation of a novel protective system for EV batteries. This system, featuring thin-walled aluminum tubes filled with Phase Change Materials (PCMs), was designed to absorb impact energy and manage thermal dissipation effectively. Through meticulous mesh sensitivity analysis and the application of material constitutive equations for aluminum 6061T6 and paraffin wax, the study successfully captured the dynamic interactions within the protective system. An empirical formulation, derived from the analysis, allowed for predicting the energy absorption capacity of the tubes across various geometrical configurations. This aspect of the study underscored the influence of geometrical parameters on the energy absorption, deflection and impact duration, offering valuable insights for battery safety design. The study included the validation of a battery pack model under impact loads, underscoring the importance of fracture analysis in maintaining structural integrity during mechanical impacts. The performance of the protective system was evaluated against real-world impact scenarios, such as side-pole collisions based on the FMVSS214 standard. The results showed a significant reduction in battery deformation with the protective system, highlighting its effectiveness in safeguarding against mechanical damages. This comprehensive study contributed significantly to the field of EV battery technology, addressing key safety challenges through a combination of experimental validation, advanced computational modeling, and innovative design. The findings offered critical guidelines for enhancing the safety and reliability of lithium-ion batteries in EVs, paving the way for more resilient and efficient energy storage solutions in the automotive industry.

AN EFFICIENT STATIC SOLVER FOR THE LATTICE DISCRETE PARTICLE MODEL (LDPM)

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[1]University of Pittsburgh

ABSTRACT

Over the last two decades, the lattice discrete particle model (LDPM) has been proven to be one of the most appealing computational tools to simulate fracture in quasi-brittle materials such as concrete, shale, masonry, high-performance cementitious composites, rocks, and polymers. The distinctive features of LDPM are its capability of materializing realistic representations of the material's internal structure and the convenience in enforcing complex constitutive laws at the 1-dimensional level of the lattice elements. Despite the tremendous advancements in the definition and implementation of the method, the solution strategies are still limited to dynamic explicit algorithms based on a central difference scheme. Disadvantages of such a solution method include prohibitive computational costs for larger simulations and challenges related to solution accuracy for quasi-static problems, due to the potential local instabilities. To this end, this study presents the development of an efficient static solver for the LDPM under various loading conditions. The development of the static solver involves three main steps. Firstly, the LDPM constitutive laws are modified to provide continuous response through all possible strain/stress states, in order to alleviate hard discontinuities. Secondly, to obtain satisfactory convergence rates, an adaptive arc-length method is developed in combination with an adaptive criterion to choose the signs of the initial increments of the iterative load factors, and an adaptive limit-unloading-reloading path switch algorithm to restrict oscillations in the global stiffness matrix. The third step aims to improve the computational efficiency of the static solution. Several advanced computational techniques including graph coloring of the Jacobian operator, automatic differentiation, and advanced matrix manipulations are employed. The performance of the proposed static solver is validated by simulating four sets of mechanical experiments: (1) unconfined compression; (2) biaxial behavior; (3) tensile splitting tests; and (4) 3-point bending tests. The numerical results from the static solution agree well with the reported test results from the experiments, and the static solution exhibits a lower computational cost than currently available explicit solutions, highlighting the potential for the proposed method to alleviate the existing challenges in solving large-scale LDPM simulations.

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AERODYNAMIC MITIGATION OF SINGLE-AXIS SOLAR TRACKERS THROUGH MACHINE LEARNING-BASED SHAPE OPTIMIZATION

Seyed Pejman Fatehi[1], Yanlin Guo[1] and Teng Wu[2]*

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ABSTRACT

Single-Axis tracking systems have recently received significant attention owing to the high efficiency in increasing the output energy by up to 25-35% when compared to fixed photovoltaic systems. However, these structures are very sensitive to the strong winds partially due to their low torsional stiffness. While the well-established bridge aerodynamic and aeroelastic theories can be leveraged to understand the underlying mechanism for wind-induced vibration of isolated single-axis solar trackers, their unique dynamic and aerodynamic features corresponding to each tilt angle that keeps changing during daily operations for tracking the sun present significant challenges of selecting effective aerodynamic mitigation measures. Specifically, the used wind mitigation strategies must be effective across the entire range of tilt angles. This study presents a novel approach to optimize the shape of aerodynamic mitigation measures utilizing machine learning to increase critical wind speed for torsional flutter. First, a multi-fidelity artificial neural network-based surrogate model is developed and trained with a combination of low and high-fidelity simulation data obtained from computational fluid dynamics (CFD) models, to minimize computational costs. Then, the surrogate model is integrated into a reinforcement learning (RL) environment, allowing the agent to adjust the shape of aerodynamic mitigation measures and observe corresponding changes in tracker aerodynamics. Finally, the optimal shape is determined by RL agent through evaluating various experiments with the objective function defined as the flutter wind speed. The effectiveness of the proposed framework is assessed through numerical simulations, where baseline solar trackers are compared with modified versions incorporating aerodynamic measures. The results demonstrate that the aerodynamic performance of the optimized trackers surpasses that of the baseline trackers within a broad of range of tilt angles.

HUMAN INTERFACE FOR INDOOR INFRASTRUCTURE MAINTENANCE USING NETWORKED SENSORS, ROBOTS, AND AUGMENTED REALITY

Alireza Fath[1], Nicholas Hanna[1], Yi Liu[1], Scott Tanch[1], Tian Xia[1] and Dryver Huston[1]*

[1]University of Vermont

ABSTRACT

This presentation describes a framework for human building interaction for home and interior structural maintenance through the use of smart technologies including networked sensors, robots, machine learning and augmented reality. Sensing and assessment for repair and maintenance of indoor infrastructure requires direct interaction between buildings and humans. Items of concern are leaks, structural issues, mechanical systems failures, vermin infestation, etc. While building assessment for maintenance is a human activity that dates back to antiquity, much of it normally requires skill and training that is beyond the grasp of the typical homeowner. Furthermore, many items of distress lie hidden beneath walls and floors. It may be possible to alleviate these sensing, assessment, and maintenance challenges through the use of advanced technologies that collect data, transmit it through networks, and reformulate in manners best understood by humans. Demonstrated techniques include the use of small robots to enter and sense in confined areas, mobile robot mounted lidar scans of structural shapes combined with assessment of deformed and misshapen conditions, moisture and gas sensing, water leak detection, network embedded machine learning including links to recommended repair options and presented to humans in augmented reality interfaces. This networked sensor system is a testbed and demonstrator for home maintenance technologies, providing a framework for Home Maintenance 4.0.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON CALIBRATION AND VALIDATION OF A COHESIVE ZONE MODEL FOR MIXED-MODE DELAMINATION IN Z-PINNED COMPOSITES

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ABSTRACT

We present the calibration and validation of a cohesive zone model for the prediction of delamination in z-pinned composite interfaces under mixed-mode conditions. Z-pins have been demonstrated to increase delamination resistance in composites through mechanisms including z-pin pull-out, bending, and fracture. The failure mechanisms depend on the magnitude of axial and shearing stresses on the z-pin resulting from crack opening and sliding between the lamina on either side of the delamination, i.e. interlaminar mode-mix. Even under relatively simple loading conditions, these complex failure mechanisms result in what could be described as a mixed-mode delamination at the laminate scale. In this study, a trilinear cohesive zone model is employed to describe the delamination of z-pinned composites under any interlaminar mode-mix. Finite element models are constructed to match experiments performed on z-pinned carbon-fiber reinforced polymer composite specimens with delaminations at the mid-length of the z-pins. Double cantilever beam and end-notched flexure test configurations provide pure Mode I and Mode II delamination conditions while mixed-mode bend tests provide intermediate mode-mix delamination conditions. The constitutive law properties are calibrated using the macroscopic force-displacement results from the experiments. Continuous property curves relating the damage evolution parameters to interlaminar mode-mix are proposed based on the calibrated values and experimental analysis of the z-pin failure mode. Results from finite element analyses of additional mixed-mode bend experiments are performed to validate the model. Analysis of the numerical and experimental tests provide insights into mixed-mode delamination propagation in z-pinned composites.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Tropical cyclone induced winds, surge-wave, flooding and impacts on infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING BUSINESS INTERRUPTION LOSS DUE TO HURRICANE WIND

Changda Feng[1], Tim Johnson[1] and Karthik Ramanathan[1]*

[1]*Verisk*

ABSTRACT

Economic losses due to natural catastrophes such as hurricanes are on the rise in recent years. In fact, NOAA indicated that there were over 18 billion dollar weather and climate disasters in 2022 making it the third most costly year on record behind 2017 and 2005 (NOAA). While the impact of climate related variables is difficult to quantify, a significant driver of these increased losses can be attributed to a substantial growth or migration in population to at risk areas along the coast. Though most of the losses come from property damage (i.e., building and contents damage), business interruption losses could represent a major part of the total economic and insured loss. Therefore, society as well as various stakeholders need to assess the business interruption risk to manage their exposure from catastrophes. While past studies have focused primarily on the quantification of property damage from hurricanes, this paper presents a methodology to quantify losses from business interruption that are typically covered in insurance policies. The methodology uses the decision tree method in a probabilistic risk analysis framework to estimate the downtime of residential homes or a business after a hurricane event. The building repair time considers the repair time for primary building damage and dependent building damage and time for business relocation if necessary. The building repair time is damage states dependent. The proposed framework also accounts for other variables that could adversely impact the downtime such as utility failure and civil authority which could vary based on the nature of a specific catastrophic event. The probabilistic risk analysis framework presented here is validated by business interruption losses from historical hurricane events.

NOAA: https://coast.noaa.gov/states/fast-facts/hurricane-costs.html

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT BAYESIAN OPTIMIZATION FOR HIGH-DIMENSIONAL UNCERTAINTY PROPAGATION IN ENGINEERING SYSTEMS

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ABSTRACT

Spatial uncertainty parameters are widely involved in actual engineering problems, and the interval field analysis method is one of the effective methods for solving these problems. Interval field analysis can be divided into interval field modeling of uncertainty in such parameters and propagation of uncertainty in such parameters by optimization methods. In recent years, the Bayesian optimization method has emerged as an efficient approach widely employed in addressing interval uncertainty propagation problems [1]. However, the variables involved in interval field modeling often exhibit high dimensionality and it is very challenging to propagate their uncertainty with Bayesian optimization methods. Therefore, this paper proposes an efficient, non-invasive uncertainty propagation method based on Bayesian optimization for the performance analysis of engineering systems described by deterministic numerical models that are expensive to evaluate. The method assumes additivity in deterministic models and employs additivity approximation methods to convert implicit functions into additive forms [2]. The methodology comprises five distinct steps in its implementation. The first step is to divide the additive function into several subfunctions according to their properties. However, its subfunctions may still have a high dimension. Therefore, the Dropout method can be used in the next step to remove the less influential variables in order to reduce the dimensionality when modeling the Gaussian process regression model [3]. For the dropped variables, they can be replaced either randomly or by selecting the current optimal values. Then, the Gaussian process regression model is built independently for each subfunction, which is generated from the initial training dataset. The fourth step is the selection of a small number of samples to be evaluated for each of the subfunctions through an iterative procedure by using an upper/lower confidence bounds function to update this Gaussian process regression model and to evaluate the range of the response. Finally, the updated Gaussian process regression model is developed based on the enhanced training dataset and its response, in which a convergence metric is used to assess whether the prediction bounds are estimated satisfactorily or not. A numerical application illustrates the applicability of the proposed method.

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Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REACTION-DRIVEN FRACTURING IN CARBON SEQUESTRATION BY MINERALIZATION

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ABSTRACT

Reaction-driven mineralization fracturing can be an effective method for carbon sequestration. Because a reaction between the host rock and CO2 produces a solid carbonate, there is no concern about leakage returning the CO2 to the atmosphere. However, the interaction of the fluid flow and reaction kinetics with the mechanics of fracture propagation on the microscale is not well understood. To address this problem, we begin with the very simplified model of a steadily propagating planar fracture. Although the fracture is idealized as semi-infinite, the load is applied over a distance L behind the tip to simulate a finite length fracture. The reaction is assumed to be a linear rate relation and to begin at a distance d behind the tip. Although we neglect any mechanical interaction between fracture propagation and the mineralization, we identify conditions for which the thickness of the precipitating layer exceeds the fracture opening. When it does the precipitating layer can drive the fracture but clogs the channel transporting the fluid. The different possibilities depend on the several non-dimensional ratios including the reaction rate to velocity of crack propagation and d/L. Then, we improve this simple model by studying a propagating finite length, plane strain crack driven by injection of CO2 laden water. We assume the CO2-water diffuses in the rock matrix in the direction perpendicular to the plane of the fracture. The CO2-water reacts with the surrounding rocks to precipitate as a new type of mineral onto the wall of the fracture surface. The precipitation can reduce the fracture opening. This reduction can increase the fluid pressure from the injection source, and promote the propagation. So, the fracture toughness and fluid viscosity interact with the precipitation kinetics from the carbonation reaction to influence the fracture propagation. We adopt an efficient numerical method for the reaction-driven fracturing problem by combining Gauss-Chebyshev quadrature and Barycentric Lagrange interpolation techniques. Scaling and numerical results distinguish different dominated regimes by the fracture toughness, the fluid viscosity, and the precipitation kinetics. These dominated regimes and corresponding transition areas can help us better understand and accelerate the carbon sequestration by mineralization.

This work was supported as part of the Center on Geo-processes in Mineral Carbon Storage, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences at the University of Minnesota under award # DE-SC0023429.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ROBUST DYNAMIC COMPENSATION OF MULTI-ACTUATOR REAL-TIME HYBRID SIMULATION TESTING OF STIFF SPECIMENS USING A COMPLIANT BEAM CONNECTOR

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ABSTRACT

Multi-actuator real-time hybrid simulation (maRTHS) is a state-of-the-art dynamic simulation method that uses multiple actuators to apply multi-axial forces or displacements onto a structural specimen for laboratory testing [1]. However, a significant challenge lies in effectively prescribing loads on stiff specimens, such as building walls or bridge piers. The primary concern revolves around managing the inherent dynamics of the loading assembly, including actuators. High-frequency vibrations within the hybrid loop are associated with actuator oil column resonance and load cell measurement noise, potentially causing simulation instability. A solution to this issue is to include a compliant mechanism in the hybrid loop, thus allowing for stable maRTHS testing [2].

This study introduces a novel virtual approach to implementing mixed-mode (combining displacement and force) control in a maRTHS test involving an axially stiff column specimen connected to a compliant beam that serves the role of a loading connector. Displacement/rotation and force/moment at the control degrees of freedom are prescribed using a series of actuators connected to the compliant beam. The dynamics of the compliant beam will be thoroughly investigated to understand the impact of its inertial effects on the simulation. For these purposes, robust adaptive model-based compensation [3] addresses tracking errors without a priori knowledge of multi-actuator-specimen interaction. This compensation technique will be decentralized and independently applied to each actuator. Additionally, we consider the nonlinear behavior of the specimen in the dynamic coupling with the complaint loading assembly.

The findings demonstrate the robustness of the proposed method, particularly in handling uncertainties within the specimen and the loading equipment, including measurement noise and multi-actuator oil-column resonance. Finally, this framework presents itself as a promising and reliable option in dynamic testing, showcasing its efficacy in complex testing scenarios.

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ASSESSING THE PERFORMANCE OF PHYSICS-INFORMED LSTM MODELS FOR SEISMIC RESPONSE PREDICTION OF NONLINEAR STRUCTURAL SYSTEMS

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ABSTRACT

Understanding the nonlinear behavior of structures during earthquakes is crucial for ensuring civil infrastructure safety. While traditional methods for predicting structural responses are accurate, they can be computationally intensive, especially when dealing with complex systems and large nonlinearities. In recent years, data-driven approaches have shown promise in providing rapid and reliable predictions for dynamic systems [1,2]. In this paper, we introduce an innovative approach using physics-informed Long Short-Term Memory (piLSTM) models to evaluate their performance in predicting seismic responses of buildings situated in Chile. We aim to assess the effectiveness of piLSTM models trained with diverse datasets that capture seismic hazard scenarios specific to Chile, inspired by incorporating fundamental principles into machine learning models.

Our research is motivated by the limitations of purely data-driven models in capturing the underlying physics of structural systems. Although LSTM networks have shown potential in learning temporal dependencies from data, their application to seismic response prediction remains challenging. By infusing these networks with physics-based constraints, our objective is to enhance their adaptability to the seismic behavior of structures. Building upon the work by Zhang et al. [3], our methodology involves training piLSTM models that integrate knowledge in structural dynamics through a physics-informed loss function.

We conduct this training using datasets representing diverse seismic scenarios in Chile, encompassing different ground motion intensities and ground conditions for a simple single-degree-of-freedom (SDOF) structure exhibiting nonlinear behavior. Our contribution lies in the model training, where we consider datasets of varying sizes and intensities. Subsequently, we evaluate the model's performance using datasets with characteristics distinct from those in the initial training, aiming to highlight the model's robustness and generalization across seismic conditions. The insights and results obtained from this study will advance predictive modeling for structural systems in seismic-prone regions.

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Machine learning applications in wind engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATING LARGE- AND SMALL-SCALE ATMOSPHERIC TURBULENCE FEATURES INTO ML-BASED WIND LOAD PREDICTION MODELS

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ABSTRACT

Atmospheric boundary layer (ABL) wind flows transport a broad range of turbulent scales that interact with the built environment. In the case of bluff-body structures (e.g., buildings), the size and duration of such turbulent eddies can influence the magnitude and spatial distribution of aerodynamic wind loads imposed on the building's envelope. Specifically, the intensity of extreme negative (suction) loads developed near flow-separated regions (e.g., roof edges/corners) of sharp-edge bluff bodies have been directly linked to the freestream turbulent characteristics of the incident wind field. Yet, recent ML-based wind load prediction tools leverage wind tunnel datasets with limited turbulent ABL flow characteristics (e.g., terrain conditions).

This presentation will highlight the development of ML-based models to infer localized wind pressure loading on bluff bodies based on 3D large- and small-scale freestream turbulent conditions. The ML models were trained using aerodynamic (wind load) data recently collected at the University of Florida (UF) boundary layer wind tunnel (BLWT). Precise adjustment of large-scale ABL turbulent flow conditions were achieved by a multi-fan array called the Flow Field Modulator (FFM), which enabled active generation of low-frequency (large-scale) flow fluctuations. Simulation of small-scale turbulence was introduced mechanically via the Terraformer, a 62 x 18 automated roughness grid located upwind of the BLWT test section. The bluff body model consisted of a 1:20 scale representation of the Texas Tech University (TTU) experimental building. The model was immersed in a broad range of large- and small-scale turbulent regimes, and flow velocity and pressure data were monitored. Sizeable geometric scale enabled higher spatial resolution of pressure sensors to better capture extreme loads produced under highly turbulent approach flow conditions.

Results from the research will help elucidate ongoing knowledge gaps associated with the role of turbulent intensity and scales on peak pressure development and the 3D fluid-body mechanisms that drive such extreme loads. While the presentation will focus on data-driven ML approaches, the results are intended to serve as a baseline to test and compare with future (and more advanced) physics-guided ML models.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT AND IMPLEMENTATION OF AN ANISOTROPIC CONSTITUTIVE MODEL FOR WOOD IN ANSYS: APPLICATION IN PREDICTING THE MECHANICAL BEHAVIOR OF A HYBRID CONNECTION FOR CROSS-LAMINATED TIMBER PANELS

Bleriot Vincent Feujofack Kemda[1] and Cristiano Loss[1]*

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ABSTRACT

As a natural material, wood presents complex inherent mechanical characteristics such as anisotropy, the difference in tensile and compressive ultimate strengths within the same direction, and ductile or brittle failure mode in different loading orientations. These characteristics make it difficult to simulate the mechanical behavior of timber members and connections, thus requiring sophisticated and advanced modeling techniques.

In this study, a three-dimensional (3D) constitutive model for wood is developed and implemented in the commercial Finite-Elements (FE) Software ANSYS through a user material (USERMAT) routine. This 3D anisotropic constitutive law was developed under the framework of continuum damage mechanics and translated from mathematical equations to a FORTRAN code. The constitutive model encompasses three main modules destined to emulate the behavior of wood from mild to extreme uni-, bi-, and tri-axial stress states. Firstly, an orthotropic constitutive law enables to capture the linear-elastic phase. Then, a yielding module was implemented. This module handles the yielding of wood based on eight stress-based functions. Lastly, an elastoplastic constitutive law was implemented to simulate the behavior of the material after yielding. Within this third module, an elastic-perfectly-plastic law is used to simulate all ductile failure modes, whereas a softening law is applied for brittle failure modes. A state variable κ, which keeps track of the loading history, is introduced to account for damage evolution in the USERMAT routine. After coding and compiling the USERMAT routine, the model input parameters, such as elastic and plastic constants, were calibrated using test results from an experimental campaign on the mechanical properties of Canadian spruce-pine-fir wood.

The constitutive model for wood was validated by developing an FE model to predict the behavior of a single dowelled-type hybrid shear connection for cross-laminated timber panels. The results from the FE model were compared to the ones from experiments on the same hybrid shear connectors. The developed FE model was able to capture the slip modulus, yield resistance, and ultimate resistance of hybrid connections with high accuracy. As a perspective, the developed FE model can be used for the assessment of the structural performance of timber connections in terms of elastic slip modulus, yield resistance, ultimate resistance, ductility in slip, as well as stress distribution and failure sequence in the wooden part of the connections.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Probabilistic learning, stochastic optimization, and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COUPLED MATLAB-ANSYS FRAMEWORK FOR THE CALIBRATION OF INPUT PARAMETERS OF A CONSTITUTIVE MODEL FOR WOOD MATERIALS USING GENETIC ALGORITHMS OPTIMIZATION

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[1]University of British Columbia

ABSTRACT

A constitutive model for simulating the mechanical behavior of wood has been developed under the commercial Finite-Elements (FE) Software ANSYS. This 3D anisotropic constitutive model was developed under the framework of continuum damage mechanics. Twenty input parameters that characterize the elastic and plastic constants of wood are required for the model. For the developed constitutive model to emulate the behavior of a given tree species and grade, the calibration of these 20 input parameters, based on experimental results, is required.

In this study, the developed constitutive model was calibrated to replicate the behavior of Canadian Spruce-Pine-Fir clear wood. The calibration was based on experimental results from compressive, tensile, and shear tests on clear wood samples. A framework was developed using MATLAB and ANSYS software to obtain an unbiased estimation of the 20 input parameters. The 20 input parameters included Young's moduli, shear moduli, and major Poisson's ratios in the longitudinal, radial, and tangential directions and planes. Specifically, a MATLAB program named "Stochastic calibrator of material models" (SCM2) was developed to run the optimization of the constitutive model's input parameters. The optimization module itself was coded in MATLAB and based on the non-dominated sorting genetic algorithm II (NSGA II). During the operation, the SCM2 invokes the NSGAII routine to guess a generation of input parameters. When the parameters are guessed, SCM2 builds an ANSYS Parametric Design Language (APDL) model where wood, which has assigned the guessed parameters, is subjected to compression, tensile, and shear stresses. Once the APDL model is built, SCM2 runs it through ANSYS Mechanical in batch mode and retrieves the load-deformation histories. These load deformation histories are then compared to experimental ones; the goodness of fit is evaluated, and the best solutions are kept. These solutions are then fed into the NSGA II algorithm to generate the next generation of input parameters. This process is followed over several generations until the acceptable error threshold of 5% is met—between the model and the experimental results.

The developed framework proved to be able to calibrate the input parameters for the constitutive model of wood efficiently and in an unbiased way. The total computational time needed to calibrate the parameters of each wood grade was below five minutes on a computer with 2 Intel Xeon Silver CPUs, 2.40GHz processors and 96.0 GB RAM. Such a framework can be expanded to the calibration of other materials and structural finite element models.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECTS OF INITIAL SAMPLING INSTANT ERROR ON PEAK GROUND ACCELERATION MEASUREMENT

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ABSTRACT

The present study explores one often-overlooked measurement error: Initial Sampling Instant Error (ISIE), and investigates the significance of this error, considering its potential impact. Over the past 50 years, seismic instrumentation has provided invaluable information, revolutionizing our understanding of earthquakes and aiding seismologists and engineers in designing safer structures, ultimately saving lives. Ground Motion Prediction Equations (GMPEs) represent a key achievement, enabling the estimation of ground motion intensity measures, such as Peak Ground Acceleration (PGA), based on general information about earthquake source, path, and site. The development of these equations relies on recorded PGAs from past earthquakes, susceptible to various measurement errors, including limited sampling frequency, aliasing, quantization error, sensor noise, clock jitter, and initial sampling instant(1). While many of these errors are thoroughly studied with established remedies, Initial Sampling Instant Error is often disregarded under the assumption of its negligibility. ISIE pertains to the error in reading PGA from a digitized signal in the time domain compared to its continuous-time counterpart obtained through Sync interpolation with the same frequency bandwidth. Though this error is inherently random, it is influenced by earthquake parameters (source, path, and site) as well as sampling rate. In this study, we analyzed a large dataset of ground motions to quantify these errors and explore their relationships with the aforementioned parameters. Based on our initial studies using 10,548 earthquake records from the PEER NGA West2 database(2), the probability of PGA error exceeding 3% due to initial sampling instant is approximately 3-4%. To further delineate the contribution of each controlling parameter to this error, we are employing machine learning techniques.

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Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS OF ARCHITECTED MICROGRANULAR MATERIALS

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ABSTRACT

Granular media possess extraordinary mechanical properties such as impact mitigation given their nonlinear grain-to-grain contact. Specifically, nonlinear contact provides a mechanism for energy dissipation and wave-propagation control under dynamic regimes, revealing mechanical behaviors not possible by conventional monolithic materials. There has been an increasing scientific interest in granular media for engineered mechanical properties, with recent work investigating various packings of custom 3D and 2D grain geometries and multi-material grains for wave guiding. Early foundational mechanics-driven granular investigations have been primarily analytical and numerical, with experiments limited to simple configurations, requiring extremely precise and carefully designed setups at the macroscale. Other efforts to fabricate complex granular materials with microscopic components have relied on self-assembly processes with low tunability and inherent defects, which inhibit prediction and control of their properties.

Here, we propose a framework inspired by architected metamaterials to design and program microgranular media with a wide range of static and dynamic properties through use of a hierarchical two-level architecture. Using microscale additive manufacturing, we fabricate custom spherical particles that possess microvoids (level 1 architecture) within a larger ideal granular packing (level 2 architecture), leading to a bulk media with tunable direction-dependent properties under compression. Developing numerical and computational models based on the Eshelby inclusion problem, we predict the multi-directional response of these architected microparticles to enable control of homogenized properties under low- and high-strain-rate regimes. Through a series of systematic nanomechanical experiments across deformation rates, we identify Poisson-like effects in the architected microparticles that lead to an increase in total grain recruitment and nonlocal contacts. Our proposed framework indicates a superior normalized stiffness and energy dissipation compared to their fully dense counterparts, providing a unique path to harness nonlocal stress redistribution for engineered nonlinear contact states. Our work aims to unlock properties unattainable from classical granular mechanics by implementing architectural design, providing a route towards lightweight, tunable, and impact-resistant architected granular metamaterials with potential applications for nonlinear waveguiding and impact mitigation.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE RELATIVE BENEFITS OF VISION AND STRAIN GAGE-BASED SHM OF MITER GATES

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ABSTRACT

SHM of miter gates must overcome several challenges related to commonly used contact sensors. Installed contact sensors must be protected from the wet environment and transmit information, requiring extensive cabling that dramatically increase SHM system cost. Due to this cost, few contact sensors are placed on miter gates which are targeted at identifying degradation in boundary conditions. Alternatively, camera sensors require no cabling, and computer vision algorithms can measure image displacements at many regions of the structure. The less-expensive installation combined with plentiful displacement measurements suggest a camera SHM system may have better value than a contact SHM system for miter gates.

This research infers damage in the entire structure using model updating with camera and strain sensor observations. Damage parameters are input to a finite element (FE) model of the structure to simulate the effects of damage. These damage parameters are updated and the FE model run until the difference between FE model outputs and measurements are minimized. A common challenge in vision-based displacement measurement is camera motion. This research uniquely addresses that challenge by parameterizing the camera motion along with damage and inferring their values concurrently. By showing the relative merits of strain sensors and camera sensors for SHM, this research proves the feasibility of vision-based SHM systems. Finally, this research predicts the current state of the downstream miter gate at The Dalles, Oregon.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A VERSATILE COMPUTATIONAL FRAMEWORK FOR CONTINUUM-KINEMATICS-INSPIRED PERIDYNAMICS USING HYPER-DUAL NUMBERS

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ABSTRACT

Continuum-kinematics-inspired peridynamics (CPD) has been recently proposed as a novel reformulation of peridynamics that is characterized by one-, two- and three-neighbor interactions.
CPD is geometrically exact and thermodynamically consistent and does not suffer from zero-energy modes, displacement oscillations or material interpenetration.
In this presentation, we introduce a computational framework furnished with automatic differentiation for the implementation of CPD.
Thereby, otherwise tedious analytical differentiation is automatized by employing hyper-dual numbers (HDN).
This differentiation method does not suffer from round-off errors, subtractive cancellation errors or truncation errors and is thereby highly stable with superb accuracy being insensitive to perturbation values.
The proposed computational framework is compact and model-independent, thus once the framework is implemented, any other material model can be incorporated via modifying the potential energy solely.
Finally, to illustrate the versatility of our proposed framework, various potential energies are considered and the corresponding material response is examined for different scenarios.

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Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL DEVELOPMENT OF A SEISMIC ISOLATION DEVICE FOR LUNAR SURFACE HABITAT RESILIENCE

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ABSTRACT

The lunar seismic environment, often overlooked, presents a critical consideration for the establishment of long-lasting surface habitats. Insights from the Apollo Passive Seismic experiment underscore the limited availability of seismic data on Moonquakes, hindering a comprehensive understanding of the associated physical phenomena. As we strive to enhance our understanding through ongoing research, the seismic risk to lunar habitats is an underrated concern. Drawing inspiration from seismic hazard mitigation measures implemented in Earth-like habitats, particularly the effectiveness of seismic isolation, our work focuses on the experimental development of a lunar surface seismic isolation device. Given the scarcity of data, our efforts aim to address the inherent challenges of lunar environmental conditions and the need to mitigate a broad spectrum of unexpected frequencies. Considerations extend to assembly, transport, and deployment, with a keen focus on minimizing mass and volume to adhere to launch restrictions. The goal is to create a functional and efficient device capable of safeguarding lunar habitats from seismic events, thereby advancing the resilience of future lunar infrastructure. Through this work, we aim to contribute to the development of sustainable and secure lunar habitats, laying the foundation for future exploration and habitation efforts.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL ALGORITHM FOR PROBABILITY OF FAILURE ESTIMATION IN STRUCTURAL ENGINEERING

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ABSTRACT

Uncertainties are a constant presence in structural engineering, impacting the design, construction, and maintenance of structures and infrastructure. These uncertainties, such as those related to the definition of material properties and element dimensions, pose a significant concern, potentially leading to the overestimation of the structural system's capacity or the underestimation of the external forces acting upon it, resulting in underestimating the failure probability.

Traditional approaches such as FORM (First Order Reliability Method) and SORM (Second Order Reliability Method) solve the problem by approximating the limit state function using first or second-order Taylor approximations. Such methods, however, may not always provide accurate results, especially when dealing with highly nonlinear limit state functions. Moreover, if a structural system has multiple failure modes, these methods are generally not applicable. In such a case, sampling methods like Monte Carlo simulations are an option. However, they can be computationally intensive, particularly for high-dimensional problems.

Based on these considerations, the purpose of this work is to introduce a novel sampling method for the estimation of the probability of failure in structural systems. Specifically, the proposed sampling method aims at accelerating the efficiency and accuracy of the estimation process.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONDITIONS FOR ONSET OF LOCALIZED DEFORMATION WITH PHASE TRANSFORMATION, WITH APPLICATIONS TO DEEP-FOCUS EARTHQUAKES

Craig Foster[1] and Javad Mofidi Rouchi[1]*

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ABSTRACT

The mechanisms causing deep-focus earthquakes, those roughly 350 km or more below the earth's surface, are poorly understood. The intense pressures rule out the possibility of the frictional sliding that dominate shallow earthquakes. These events cannot be observed directly, but understanding can be attained through a combination of remote sensing, small-scale laboratory experiments at high temperatures and pressures, and numerical modeling. We focus here on the numerical portion of this research.

Several theories have been proposed to explain these events. One of the leading theories is that of transformational faulting. Phase transformation in minerals, particularly olivine to spinel transformations at high temperatures and pressures, lead to compaction and weakening of the material that can lead to faulting. Laboratory experiments suggest that the material localizes in very narrow bands, initiated at stress concentrations near inclusions, grain boundaries, and other inhomogeneities.

Phase transformation in bulk material has been modeled in several ways. Here, we model as a rate process [1]. In this presentation, we examine the mathematical conditions that determine when it is favorable for phase transformation and deformation to localize into narrow bands rather than transform diffusely within a crystal. We extend the classical bifurcation theory [2] developed to capture localization in deforming materials to the case that includes phase transformation and thermal effects. We then develop numerical algorithms for testing these conditions in the case.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATISTICAL LINEARIZATION SOLUTION TREATMENT OF STOCHASTICALLY EXCITED NONLINEAR SYSTEMS: AN ALTERNATIVE PERSPECTIVE BASED ON COMPUTATIONAL ALGEBRAIC GEOMETRY

Ioannis Kougioumtzoglou[1], Vasileios Fragkoulis[2] and Ioannis Petromichelakis[1]*

[1]Columbia University
[2]University of Liverpool

ABSTRACT

Abstract
Statistical linearization has been one of the most versatile, approximate, approaches for determining the stochastic response of nonlinear systems in a computationally efficient manner (e.g., [1]). The main objective of the approach relates to replacing the original nonlinear system by an equivalent linear one for which an analytical solution treatment is possible. This is done, typically, by minimizing the mean square error between the two systems, yielding a set of nonlinear algebraic equations to be solved for the system response stationary second-order statistics (i.e., covariance matrix). In this regard, a wide range of numerical optimization schemes can be employed for determining the system response covariance matrix (e.g., [2]). However, there is no guarantee, in general, about existence and convergence to a (potential) global minimum. In fact, the performance of most standard optimization algorithms depends, significantly, on the choice of the starting point, and deteriorates for strongly non-convex objective functions.

To address this challenge, an algebraic geometry technique is developed within the statistical linearization solution framework for determining the stochastic response of nonlinear systems. Specifically, considering system nonlinearities of polynomial form, and resorting to computational algebraic geometry concepts and tools, such as Gröbner basis (e.g., [3]), it is shown that the entire solution set of the resulting system of coupled multivariate polynomial equations is determined exactly. The reliability of the developed technique is demonstrated by considering an indicative numerical example and by comparing both with relevant Monte Carlo simulation data, and with results obtained by the standard statistical linearization approach.

References
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[3] D. A. Cox, J. Little, D. O’shea, Using Algebraic Geometry, vol. 185, Springer Science & Business Media, 2006.

PERFORMANCE-BASED SUSTAINABLE BRIDGE DESIGN FOR SEISMIC AND FIRE HAZARDS

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ABSTRACT

Multihazard risk-based design is a novel approach to bridge engineering that aims to enhance structural performance through the holistic consideration of multiple hazards and their interactions (if any). Within this context, we propose a multihazard optimization methodology to minimize seismic and fire consequences on bridges. Fire and earthquake can generally be considered non-interacting hazards for bridges: an earthquake would rarely trigger a bridge fire, whereas a negligible probability might characterize the simultaneous occurrence of an earthquake during a vehicle-induced fire. However, design philosophies for different hazards can result in competing demands for structural design (reflecting asynergies in the structural response to different hazards). Optimization techniques enable dealing with this trade-off and exploiting cross-hazard synergies.

In the proposed methodology, consequences are quantified probabilistically in terms of residual functionality (i.e., "robustness" in the context of resilience analysis). The seismic residual functionality is computed by combining conventional fragility analysis and component damage ratios. On the other hand, the fire residual functionality is quantified through a novel methodology named the Consequence-oriented Fire Intensity Optimization (CFO) approach. The latter acknowledges that the fire hazard is defined by the features of the structure it affects and can, therefore, be treated as a design variable to optimize.

A multiobjective optimization algorithm searches for solutions that maximize 1) seismic residual functionality and 2) fire residual functionality. In this process, we use surrogate models trained on finite element analyses to aid computational efficiency. The optimization problem provides a Pareto front of solutions that should be ranked according to stakeholders' preferences. Thus, acknowledging that sustainability and environmental impacts are general concerns across hazards, we propose an embodied-carbon-based ranking criterion to aid the decision-making process. Implementing this criterion also sheds light on synergies and asynergies between design for multihazard resilience and sustainability.

As an illustrative example, we consider innovative steel girder bridges endowed with low-frequency sinusoidal (LFS) webs (wavelength in the order of a meter). This system exhibits enhanced shear strength, material efficiency, and fatigue behavior compared to conventional flat web and corrugated girders. First, we use sensitivity analysis to study the synergies and asynergies between LFS bridges' seismic, fire, and sustainability performances. Then, we apply the proposed methodology to calculate optimized structural forms (e.g., girder depth, sinusoid wavelength, and amplitude) and discuss optimal decision-making from various stakeholders' perspectives.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DEEP MATERIAL NETWORK USING MICROPOLAR MECHANICS

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ABSTRACT

The deep material network (DMN) is a recent paradigm that combines homogenization techniques with neural networks to rapidly predict the response of composite materials with high accuracy. These reduced order models have analytical formulas at their core, making them capable of extrapolating to other constitutive equations after training only once on linear elastic data. Thus far, the approaches to DMN use classical continuum mechanics to construct the network. Here we study the DMN idea extended to micropolar mechanics, which generalizes the classical continuum to include not only the three displacement degrees of freedom at every point, but three additional microrotation ones too. In the micropolar setting, intrinsic length scale effects representing the microstructure of the material arise naturally. These length scales are not captured in the classical models, so it is of interest to have a DMN sensitive to these effects. The homogenization building block of the micropolar DMN is derived via asymptotic homogenization applied to a simple micropolar laminate. This formula is a function of the normal vector of the laminate plane and the volume fraction; both of which will serve as network parameters to be learned in the training process. The training data is generated using linear elastic micropolar fast Fourier transform (FFT) direct numerical simulations (DNS). Then, using a nonlinear micropolar constitutive model, the micropolar DMN is shown to extrapolate accurately without retraining. The reference DNS used as our metric for accuracy is a nonlinear extension of the micropolar FFT DNS.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PARAMETRIC ANALYSIS OF ARCHAIC STEEL COLUMNS

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[1]Old Structures Engineering

ABSTRACT

The capacity of existing columns is a major concern during the investigation and alteration of existing steel-frame buildings. Columns are an integral part of analysis to find the load capacity of a frame, so their analysis is always part of determining the feasibility of building alteration and reuse. Because the United States did not have a national steel code until 1923 and did not have regional building codes until the 1920s, column capacities were calculated using local (municipal or state) building codes and steel manufacturers' recommended specifications. There were multiple column formulas used in the United States before the first edition of the national specification by the American Institute for Steel Construction was published in 1923, and there have been fifteen revisions to that code since.

Early column analyses, including the early editions of the AISC specification, provided only axial strength, based on only the column section properties and the unbraced length. Later analyses included P-Δ effects of combined axial load and moment through the use of interaction formulas, and the effect of column-end fixity and sidesway through the use of the effective length factor K. The strength and ductility of new steel material improved over the course of the twentieth century, so the yield and ultimate stresses of steel have increased, but this generally does not change the relative differences between new and old formulas for a specific column. Archaic columns – those designed before current codes – may differer substantially from modern designs.

For a given physical column (and therefore a given material yield strength, material ultimate strength, sectional area, and moments of inertia) the variable external constraints are the physical unbraced length, the end-fixity conditions for the column, and the applied axial load and moment. The length and end conditions can be combined into a single effective-slenderness factor, called KL/r in AISC notation, leaving only three independent parameters. By varying these three parameters and comparing the results for the old codes to the current code, it is possible to determine which conditions will result in the old designs being unconservative relative to current code. This allows for easier and more accurate analysis of existing buildings.

This presentation will show the relationship between original analysis and current-day analysis for varying ratios of axial load to bending, and varying values of effective slenderness.

Structural reliability, bridges, and truck loads
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECENT DEVELOPMENTS IN WIM DATA GATHERING AND APPLICATION

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ABSTRACT

Weigh-in-motion (WIM) records of truck weights have been used in code calibrations for bridge design and evaluation. Some of today's WIM datasets are able to offer more information than those gathered around 15 or more years ago, and of course they are significantly more advanced that those collected via stationary weighing. Examples are vehicle speed, higher resolution of the truck arrival time, more vehicles recorded other than trucks, etc. More WIM stations have been updated to provide these useful features. Such additional information can help further advanced studies for enhanced specifications of bridge design and evaluation. They can help eliminate many assumptions used in the past efforts of code calibration.

This presentation will exhibit recent developments in the direction of maximizing the use of WIM data in bridge engineering by taking advantage of these new features, to enhance national and state specifications for bridge design and evaluation. For example, higher timestamp resolution available today has been made it possible to understand the relative positions of trucks in a platoon on bridge spans of various lengths. This understanding helps to more reliably assess the total force effects of all contributing trucks on the span, without any assumptions as to how much they might be correlated in weight, configuration, position, etc. These new developments have advanced and will further push forward the effort for data-based specifications and elevated bridge safety.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A HYBRID DEEP LEARNING FRAMEWORK ENABLING EDGE INTELLIGENCE FOR DATA ANOMALY DETECTION IN SMART STRUCTURAL HEALTH MONITORING SYSTEMS

Shuaiwen Cui[1], Hao Fu[2], Xiao Yu[1] and Yuguang Fu[1]*

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[2]Chongqing University

ABSTRACT

This study explores an alternative to the existing centralized process for data anomaly detection in modern Internet of Things (IoT)-based structural health monitoring (SHM) systems. An edge intelligence framework is proposed for the early detection and classification of various data anomalies facilitating quality enhancement of acquired data before transmitting to a central system. State-of-the-art deep neural network pruning techniques, depthwise separable convolution, and quantization-aware training are investigated and compared aiming to significantly reduce the network size so that it can run efficiently on resource-constrained edge devices such as wireless smart sensors. Furthermore, a hierarchy decomposition (HD) method is applied, which uses a well-designed file structure to decompose and store the CNN model parameters. The proposed edge intelligence framework is first examined numerically and eventually deployed in wireless smart sensors to timely deal with a faulty sensor, minimizing the wasteful use of power, memory, and other resources in wireless smart sensors, increasing efficiency, and reducing maintenance costs for modern smart SHM systems.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN MODAL ANALYSIS BASED ON SPURIOUS MODE IDENTIFICATION AND BAYES-MODE-ID

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[1]City university of Hong Kong

ABSTRACT

Both spurious and physical modes present as peaks in spectra. It is crucial to identify which peaks belong to spurious or physical modes. The traditional spurious identification methods result in a heavy computation burden and low efficiency. To release calculation burden and improve efficiency, a novel frequency-domain-decomposition-based spurious mode identification method is developed in this paper. The ‘merged value’ through combining the uncertainty of modal coordinate and the collinearity of modal phases for each spectrum peak is used as the index for spurious and physical modes identification. The uncertainty of modal coordinate for each peak is calculated based on uncertainty propagation theory, and the collinearity of modal phases is obtained through computing the coefficient of variation for the tangent values of the phases. Then, the identified spurious modal responses are cut off from the raw measured responses. After that, a Bayesian modal-component-sampling system identification (Bayes-Mode-ID) method is used to identify the modal parameters for the physical modes of the target structure. An experimental case study on a two-story steel frame was carried out to illustrate the procedures of the whole methodology. The physical and spurious modes are clearly distinguished with the proposed spurious mode identification method, and the modal parameters for each physical mode are obtained with Bayes-Mode-ID method.

Keywords: spurious mode identification, physical mode identification, uncertainty propagation, collinearity of modal phases, Bayes-Mode-ID

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXTREME SPARSIFICATION OF PHYSICS-AUGMENTED NEURAL NETWORKS FOR INTERPRETABLE MODEL DISCOVERY IN SOLID MECHANICS

Jan Niklas Fuhg[1], Reese Jones[2] and Nikolaos Bouklas[3]*

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ABSTRACT

Data-driven constitutive modeling with neural networks has received increased interest in recent years due to its ability to easily incorporate physical and mechanistic constraints and to overcome the challenging and time-consuming task of formulating phenomenological constitutive laws that can accurately capture the observed material response. However, even though neural network-based constitutive laws have been shown to generalize proficiently, the generated representations are not easily interpretable due to their high number of trainable parameters. Sparse regression approaches exist that allow for obtaining interpretable expressions, but the user is tasked with creating a library of model forms which by construction limits their expressiveness to the functional forms provided in the libraries. In this work, we propose to train regularized physics-augmented neural network-based constitutive models utilizing a smoothed version of L0-regularization. This aims to maintain the trustworthiness inherited by the physical constraints, but also enables interpretability which has not been possible thus far on any type of machine learning-based constitutive model where model forms were not assumed a-priory but were actually discovered. During the training process, the network simultaneously fits the training data and penalizes the number of active parameters, while also ensuring constitutive constraints such as thermodynamic consistency. We show that the method can reliably obtain interpretable and trustworthy constitutive models for compressible and incompressible hyperelasticity, yield functions, and hardening models for elastoplasticity, for synthetic and experimental data.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SHOCK DYNAMICS OF ARCHITECTED MATERIALS

Shengzhi Luan[1], James Guest[1] and Stavros Gaitanaros[1]*

[1]Johns Hopkins University

ABSTRACT

Recent advances in additive manufacturing have facilitated the design of novel architected materials that exploit control over material mesostructure, to outperform typical cellular solids and produce effective properties, including stiffness and strength, that often reach theoretical upper bounds. However, the corresponding gains at high-loading rates remain largely unexplored. It has been established that at above a certain critical impact velocity, the compressive deformation of cellular solids changes to a shock-type behavior, with a sharp front forming at the impact plane and subsequently traversing the material. In this regime, the stresses at impact and distal ends are connected through the classic jump conditions of shock physics. We will present numerical and theoretical techniques that aim to quantify the effect of topology on the shock dynamic behavior of architected materials, and in particular on the stress-velocity Hugoniot and associated energy absorption capacity. First, we examine the dynamic response of two architected materials with distinct topologies but sharing the same density and identical quasi-static strength. The results indicate that as the loading rate increases the effect of material architecture decreases significantly. We will also describe ongoing efforts to develop analytical formulas that are able to capture the dynamic stresses of architected materials and the associated Hugoniot curves, by using solely their quasi-static response and the jump conditions connecting mass, linear momentum, and internal energy across the propagating shock.

Structural reliability, bridges, and truck loads
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PARAMETRIC STUDY OF ROTATIONAL RESTRAINT IN PRESTRESSED CONCRETE BRIDGE JOINTS

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ABSTRACT

Prestressed concrete bridges are a common method of bridge construction, yet there remains a lack of research regarding the rotational restraint contribution of the girder-to-column joint. This joint consists of the cast-in-place concrete diaphragm, dowel bars, shear key, and bent cap. In some designs, the ends of the prestressed girder are encased in the concrete diaphragm that is connected to the bent cap through dowel bars and a shear key. The rotational restraint of this connection directly influences the effective length factor (k factor) in bridge column design. Current practice is to adopt a conservative approach and treat the joint as a pinned connection, thus a k factor of 2. However, there may be significant rotational restraint provided by the connection, reducing the k factor closer to 1. The current pinned assumption may lead to the overdesign of these prestressed bridges, raising concerns about efficiency and resource utilization. This study presents a comprehensive parametric analysis conducted through the use of FE models aimed at understanding the impact of various parameters—such as girder size, diaphragm width, skew angle, and column size—on the rotational restraint of the girder-to-column joint in prestressed concrete bridges. Finite Element (FE) models have been developed using the commercial ANSYS software. The determination of rotational restraint involves analyzing the initial slope of the moment-rotation curve of the modeled joints. The findings of this research are expected to contribute significantly to optimizing bridge design practices, potentially leading to more cost-effective and resource-efficient construction methodologies.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REDUCED-ORDER PHASE-FIELD MODELING FOR CONTROLLED MICROSTRUCTURE IN ADDITIVE MANUFACTURING

Zhengtao Gan[1]

[1]*The University of Texas at El Paso*

ABSTRACT

One of the significant challenges associated with Laser Powder Bed Fusion (L-PBF) is the evolution of microstructures (i.e., crystalline grain structures), which has a significant impact on the final material properties. To address this challenge, our study presents a physics-guided and machine-learning-aided approach for optimizing scan paths to achieve the desired microstructure outcomes, particularly focusing on the generation of equiaxed grains which are desirable for enhanced material properties. We utilize phase-field (PF) modeling, a physics-based computational method, to gain insights into microstructure evolution. The high computational costs associated with PF modeling can be mitigated by employing machine learning reduced-order or surrogate models. We will introduce two approaches for accelerating phase field models. The first one is a physics-embedded graph network, which leverages an elegant graph representation of the grain structure and embed the classic PF theory (e.g., Allen-Cahn equation) into the graph network. The second approach is by training a surrogate machine-learning model using a three-dimensional (3D) U-Net convolutional neural network. This approach enables the learning of microstructure evolution in a supervised manner, with the machine learning model being able to predict crystalline grain orientations with high accuracy based on the initial microstructure and thermal history. The training data pivotal for our machine-learning model is generated from single-track, single-layer PF simulations, under various process parameters. We aim to capture the essential characteristics of grain structures in a compact representation. This transformation significantly reduces the computational burden and provides a structured search space for optimization.

Reference:
Xue, T., Gan, Z., Liao, S. and Cao, J., 2022. Physics-embedded graph network for accelerating phase-field simulation of microstructure evolution in additive manufacturing. npj Computational Materials, 8(1), p.201.

PROBABILISTIC DEFLECTION MODEL AND FRAGILITY ESTIMATION OF STEEL I-SECTION BEAMS UNDER FAR-FIELD DETONATIONS ON ITS WEAK AXIS

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ABSTRACT

Considering the increasing threat of blast loading attacks on structures and the inadequacy of existing design codes, this study aims to develop a probabilistic deflection model for steel I-section beams. To achieve this, a dataset comprising 50 LS-DYNA numerical simulations is generated through a systematic numerical experimental design process. These simulations, based on finite element (FE) analysis, expose realistic material and geometrical variables to varying combinations of detonation mass and stand-off distance. Prior to constructing the probabilistic deflection model, a rigorous numerical validation procedure is conducted to ensure the accuracy and reliability of the simulations. The Bayesian approach is then employed to estimate the unknown model parameters and their associated posterior statistics. The developed probabilistic model incorporates dimensionless correction terms derived from principles of mechanics, engineering expertise, and relevant literature. Furthermore, a case study is presented, utilizing fragility analysis to depict the relationship between the axial load ratio (ALR) and the damage index (DI). This graphical representation serves as a valuable tool for assessing the structural integrity of the steel member under consideration. It empowers clients and engineers to make informed decisions regarding building occupancy and offers insights into retrofitting options that can preserve structural integrity, thus mitigating the need for complete demolition or rendering the building unusable. This research contributes to advancing the field of probability and reliability in structural engineering, particularly in the context of blast-induced loading scenarios.

Structural reliability, bridges, and truck loads
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL RELIABILITY ANALYSIS IN BRIDGE DESIGN AND EVALUATION

Lubin Gao[1]*

[1]USDOT/Federal Highway Administration

ABSTRACT

Structural reliability theory has been applied in the development of design and evaluation specifications for highway bridges in the United States for almost 40 years. During this course, reliability analysis has improved our understanding of inherent bridge safety margin in the preceding design and evaluation methodologies, and these reliability-based specifications provide better consistency and uniformity in new bridge design and in-service bridge evaluation. However, uncertainty quantification of variables such as truck loads still needs further research for improvement. This talk will focus on the challenges we have seen in practice and discuss potential opportunities to overcome them.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CNN-BASED SURROGATE FOR THE PHASE FIELD FRACTURE MODEL AND ITS APPLICATION IN INVERSE DESIGN OF COMPOSITE MATERIALS

Yuxiang Gao[1], Soheil Kolouri[1] and Ravindra Duddu[1]*

[1]Vanderbilt University

ABSTRACT

Predicting the fracture strength of heterogeneous composite materials based on microstructure information using the phase field fracture model presents significant computational challenges, which are further exacerbated with iterative trial-and-error strategies that extend the cost of inverse design. Although multiscale mechanics models have addressed these issues, the need for optimizing design-space parameters requires computationally-inexpensive surrogate models based on machine learning (ML) approaches. Recent developments in ML show potential for speeding up material design and discovery (Gu et al., 2021); however, its use in inverse design of material microstructures to enhance mechanical properties has not been fully explored, particularly for materials governed by constitutive damage models. Our research aims to address this gap by introducing an innovative inverse design framework that combines a convolutional neural network (CNN) with a differentiable simulator for microstructure configuration. The CNN model effectively predicts stress fields and the simulator translates material design parameters into an image format, retaining essential gradient information. This combination allows for the efficient optimization of fiber-reinforced composite designs using gradient ascent methods.

In our presentation, we will first present the details of our CNN-based model for predicting phase-field damage in composite microstructures (Gao et al., 2023). We will describe the re-training of this model for stress field prediction, the procedure to determine peak loads, and data augmentation to enhance prediction accuracy. Our results show notable improvements in peak load prediction accuracy with the stress field compared to the damage field. Next, we will present the details of the differentiable simulator that converts microstructure design parameters (e.g. fiber positions and sizes) into CNN model compatible images without losing gradient data. Finally, we will discuss an inverse design framework combining the above developments to optimize design parameters of composite microstructures based on peak load predictions. Our computations demonstrate that our framework consistently enhances the strength of microstructures beyond the limits of the training set, thus highlighting its viability.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE ELEMENT ANALYSIS OF THE INFLUENCE OF POROSITY ON STRIKE-SLIP SURFACE FAULT RUPTURE

Fernando Garcia[1]

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ABSTRACT

The discrete element method (DEM) is widely used in the fields of structural geology and tectonics to simulate the formation of fault-induced geologic features, such as folds, shear zones, and surface ruptures. With few exceptions, the vast majority of these simulations have focused on dip-slip fault rupture, with few exceptions of strike-slip fault rupture. Strike-slip fault rupture is particularly difficult to model with DEM due to it being an inherently three-dimensional (3D) boundary condition with in-plane and out-of-plane movement. 3D models often require millions of individual grains to capture the finest details of developing shear zones. Fortunately, high performance computing makes this entirely possible. This study utilizes high performance computing with DEM to simulate strike-slip fault rupture in dense, medium, and loose analogue soils in 3D using non-spherical particles. The results of the shear zones that develop during rupture are analyzed in plan view from above and from the side view to develop a comprehensive comparison with features observed in nature through post-earthquake reconnaissance activities. In the dense soil, multiple shear zones tend to propagate in opposing directions over a very wide area, with each shear zone being highly localized and bounding relatively undeformed soil between them. Rupture tends to be more concentrated from bedrock to ground surface in the loose soil. The ground surface tends to heave over a broad area in the dense soil, while the loose soil exhibits both surface depressions and upheavals in different locations along the surface fault trace. The dependence of surficial fault features on the porosity of the analogue soil reflects the development of en-echelon shear zones versus more broadly deformed rupture zones seen in case histories from the 2019 Ridgecrest and 2010 Darfield earthquakes. Simulations are performed with three different particle sizes to evaluate the role of grain size on the results. The total number of particles ranges from the order of 1 million with the coarsest particles to over 86 million with the finest particles, making these simulations the largest discrete element simulations of fault rupture to date.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN APPROACH FOR DESIGN OF MULTI-MATERIAL WELLBORE PLUG PLACEMENT PROCESSES ACCOUNTING FOR UNCERTAINTY

Carlos Garcia Verdugo[1], Eilis Rosenbaum[2], Matthew Grasinger[3], Julie Vandenbossche[1] and John Brigham[1]*

[1]University of Pittsburgh
[2]National Energy Technology Laboratory
[3]Air Force Research Laboratory, Material & Manufacturing Directorate

ABSTRACT

Plugging orphaned and abandoned wells with a combination of bentonite clay gel and cement slurry has emerged as a cost-effective strategy for preventing the migration of unwanted fluids and ensuring zonal isolation. Despite the efficacy of this approach, challenges persist, such as the potential loss of the bentonite component of the plug and unexpected leakage. Prior work has shown the capability of the Lattice Boltzmann Method (LBM) to estimate the resulting plug positioning and other important factors when placing layered multi-material plugs comprised of bentonite clay gel and cement slurry (Garcia, et al. 2023). The current research builds upon this previous work by expanding the plug placement analysis, and ultimately design approach to incorporate the ubiquitous uncertainty that exists in plug placement processes, including variability in wellbore conditions (e.g., borehole diameter) and process parameters (e.g., pumping velocity). As previously, the LBM is used as the deterministic solver to simulate the effects of the rheological properties of cement slurry and bentonite clay gel, as well as wellbore condition in wellbore plugging operations, due to its capability to capture the complex fluid interactions inherent in multi-material systems. The LBM is then combined with a Monte Carlo approach that uses response surface modeling for computational efficiency to evaluate the effects of uncertainty in the system parameters on the plug placement process. In addition to the details of the analysis strategy, results will be presented examining the effects of the rheological properties of cement slurry and bentonite during realistic plug placement scenarios accounting for uncertainty. Moreover, this analysis will be used to explore the design elements of the plugging process (e.g., material properties, pumping velocity, etc.) that are needed to ensure reliable plug placement to achieve zonal isolation.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LUNAR AND MARTIAN REGOLITHS: CHARACTERIZATION AND SUITABILITY FOR CONSTRUCTION

Nishant Garg[*1]

[1]*University of Illinois Urbana-Champaign*

ABSTRACT

The establishment of human habitats on the Moon and Mars is the next step in space exploration. To realize this vision, construction materials must be harvested from locally available resources, such as the Lunar and Martian regolith. In this talk, I will share our preliminary results on a series of 6 extra-terrestrial regolith simulants. Briefly, we perform a detailed mineralogical characterization to understand the phase assemblage. Following this analysis, we evaluate their suitability to participate in an alkali-activation reaction, which can lead to their potential use as construction materials. We find that understanding the fundamental mineralogy and chemistry of such regoliths is a prerequisite for in situ resource utilization.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MONITORING VIBRATION RESPONSE OF THE SHIELD MACHINE: APPLICATION TO REAL-TIME GROUND PROPERTY DETECTION

Ziheng Geng[1] and Chao Zhang[1]*

[1]*Hunan University*

ABSTRACT

The vibration response of the shield machine is an outcome of the cutter-ground interaction, thus holding huge potential in ground property detection. However, its potential remains largely unexplored due to the limited measured data. Here, a comprehensive dataset is provided to incorporate the vibration response of an Earth Pressure Balance (EPB) shield during its traversal varying ground conditions. It is collected from a vibration monitoring system deployed on the Changsha Metro Line 1 North Extension. The analysis shows that the vibration magnitude of the shield machine increases with the advance rate, but the rate of increase is dictated by the ground properties, with a higher rate in harder rock. Also, a series of impulses induced by the disc cutter's penetration into the ground interface are observed in the vibration waveform under composite ground. Building upon these findings, a novel framework is proposed to harness the vibration response of the shield machine to detect the excavated ground properties. Specifically, a support vector classifier is developed with inputs of mean vibration amplitude over 100-140 Hz and advance rate to identify various ground classes. Meanwhile, mean square frequency and spectrum flatness are utilized to quantitatively distinguish between the spectra of composite and homogenous ground. The reliability of the proposed framework is assessed with borehole data, demonstrating its ability to fully capture the excavated ground properties. Additionally, the proposed framework is utilized to predict the ground properties between boreholes, with muck samples used for validation, highlighting its potential in refining the initial geological profile.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADAPTIVE ROBOTICS FOR AUTONOMOUS SURFACE CRACK REPAIR

Joshua Genova[1] and Vedhus Hoskere[1]*

[1]*University of Houston*

ABSTRACT

In the realm of infrastructure maintenance, addressing the persistent challenge of surface crack detection and repair necessitates innovative solutions. Current robotic technologies for crack repair, while advanced, exhibit limitations in adaptability and precision. Some systems can fill cracks but lack complete autonomy, requiring human intervention. Others add a seventh axis of motion for z-axis movement in the end-effector but lack material extrusion adaptability for varying crack sizes. Automated guided vehicles have also been employed for road crack repair; however, their efficacy was limited to operations in the x-y plane and only tested with paint droplets. Advancements in deep learning and computer vision for crack detection and estimation offer a promising avenue to enhance these methods. Accurate detection and segmentation of cracks using these technologies enable the determination of their width, facilitating precise adjustments in robot and actuator settings for more effective surface crack repairs. However, a significant limitation arises from the inherent trade-off between the field of view and the accuracy of measurements when using cameras for deep learning and computer vision approaches. To address this, our project innovates by combining RGB camera technology with a laser profiler. The RGB camera is used for crack segmentation, while the laser profiler accurately measures the dimensions of the crack. This dual approach ensures both accurate detection and precise measurement, vital for effective repair. The novelty of our project lies in its dynamic adjustment of concrete filler extrusion, based on real-time crack measurements obtained from RGB images complemented by laser profiling. Additionally, a Proportional-Integral-Derivative (PID) controller with gain scheduling is designed for precise extrusion control. This setup enables dynamic adjustments in material extrusion, finely tuned to each crack's specific requirements. It effectively handles varying sizes within the same path, thereby significantly enhancing the precision and adaptability of the repair process. Overall, this integrated approach represents a major leap forward in autonomous infrastructure maintenance technology, significantly enhancing the precision, adaptability, and effectiveness of surface crack repairs.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A STUDY ON THE DYNAMIC BEHAVIOUR OF A FULLY SATURATED IDEALIZED 2D EMBANKMENT

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ABSTRACT

The presence of a saturated medium in a dam embankment can significantly affect the wave propagation through it. For an efficient seismic risk analysis of an embankment dam, a multi-physics approach must be adopted. Along with the influence of water, the topographical irregularity of the dam also alters its seismic response. The wave propagation characteristics through a saturated porous medium and effects by the topographical features have been individually studied in the past. In the present study, the combined influence of surface irregularities and saturation is analyzed by studying the dynamic response of an idealized saturated embankment subjected to seismic waves and comparing the response with that of an identical dry embankment. The variation in amplification with respect to different geometric parameters of both dry and wet embankment mediums is evaluated. Apart from the changes in dam geometry, the effect of porosity and permeability are also studied. We observe that changes in permeability cause a non-monotonic variation in amplification and result in an optimum permeability where the least wave amplification occurs. This can be attributed to the increased viscous coupling between the soil and fluid phase under low permeability and the generation of slow p waves at higher permeability.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BIM DEVELOPMENT WITH DAMAGE DETECTIONS BASED ON UAV

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ABSTRACT

Traditional bridge maintenance methods rely on manual inspections and labor-intensive process, often lacking sustainable long-term maintenance solutions, especially for bridges in services. Therefore, a new approach is needed for the inspection, maintenance, and systematic evaluation of aging infrastructures. In this study, a detailed solution is suggested to improve the next-generation bridge maintenance process and reliable decision-making using the digital twin model concept. Unmanned Aerial Vehicles (UAVs) are employed to capture RGB and thermal images. The acquired 2D images are converted into 3D Point Cloud Data (PCD) for the generation of a base Building Information Modeling (BIM) model. The UAV-acquired 2D RGB and thermal images are also utilized for deep learning-based damage detection and classification. For damage conditions requiring width or area calculations according to the bridge inspection diagnostic form, a semantic segmentation algorithm is applied to detect surface damage areas of the bridge. Civil infrastructures face the challenge of managing high-density PCD for fine crack detection, which leads to inefficient management. Thus, this study introduces a method involving the creation of boundary boxes around classified damaged areas in 2D images and then generating PCDs respectively from each bounded area. Edges are then detected for damaged PCD, and surface planarization is performed based on the detected each area. The volume difference between non-damaged and damaged PCDs is then calculated to precisely define the damaged area. To implement a digital twin model, the defined damage information is mapped onto the BIM model. For this purpose, global coordinates obtained from UAV for damaged areas are transformed into local coordinates on the BIM. The framework developed in this study enables efficient damage assessment, offering the potential for effective management of civil infrastructures.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL PERFORMANCE SENSITIVITY OF BUILDINGS TO WIND-INDUCED INTERFERENCE EFFECTS IN GROWING CITIES

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ABSTRACT

Cities as complex network of physical systems such as buildings, infrastructure, and communities are vulnerable to environmental risks like strong wind events. To ensure timely recovery of cities in the aftermath of windstorms, good understanding of vulnerability of city's individual components as well as their interactions is necessary. High-rise buildings are one of the major components of highly populated cosmopolitan areas that are specifically vulnerable to wind loads due to their flexibility and susceptibility to aerodynamic instabilities. Currently, as part of design process of a new building, wind tunnel experiments or computational fluid dynamics (CFD) simulations might be used to quantify wind-induced interference effects on the performance of the new building or on the pedestrian comfort and pollution dispersion in the street canopies that the building is added to. However, there are certain limitations associated with wind tunnel experiments and CFD simulations in terms of cost, accessibility, and extensibility of these methods that restrict their practical application. The objective of this study is to provide useful insight into the understanding of the wind-induced interference effects on the structural performance of an example high-rise building to help design professionals optimize their experimental or numerical modeling strategies of similar buildings by reducing the time and cost associated with their chosen approach. This presentation provides results of a case study that investigates sensitivity of the structural performance of a 40-story steel moment resisting frame to wind-induced interference effects in the presence of an identical neighboring building. The case study building is subjected to wind loading histories obtained from Tokyo Polytechnic University aerodynamic database for two adjacent tall buildings. Structural response measures for strength, serviceability, and inhabitability of the building are obtained from the pre-standard for wind performance-based engineering. Different building configurations are considered as part of the investigations. The distance between the buildings, building orientation, and the wind approach angle are the variables that make up different configurations. Sensitivity of the building structural performance measures to each of these variables are presented as part of the results.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENGINEERED BIOMOLECULES FOR SELF-HEALING RESILIENT INFRASTRUCTURE MATERIALS

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ABSTRACT

There exist in nature a number of biological inorganic-organic composites with properties far exceeding those of conventional engineering materials. The superiority observed in these biological materials is attributed to the role of certain biomolecules directing the nucleation, microstructure formation, and macroscale properties of the materials. Motivated by nature, there have been extensive research efforts in the materials science and engineering communities aimed at exploiting biomolecules in the development of materials with desired characteristics.

In this presentation, the effects of two modifying agents, including sodium dodecyl sulfate (SDS) and lignin, on the self-healing performance of several biomolecules in cementitious systems are investigated. Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), x-ray microcomputed tomography, and mechanical testing were employed to assess the microstructure and performance of the healing products. The results show an increase in the interfacial strength of engineered biomolecules, which results in enhanced self-healing behavior. The influence of the modifying agents on the molecular structure and physicochemical properties of biomolecules is discussed.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ITERATIVE ACTIVE LEARNING FOR DAMAGE SEGMENTATION OF CONCRETE DAM STRUCTURES THROUGH HUMAN-AI COLLABORATION

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ABSTRACT

Computer vision and supervised deep learning methods have been extensively applied to perform damage detection of various civil infrastructures. However, one main challenge associated with supervised deep learning methods is the need for labeled data for model training. For civil infrastructures, such as concrete dams considered in this study, publicly available datasets with relevant damage cases are scarce, and manual pixel-level labeling can be very time-consuming and costly. In this presentation, we introduce an iterative active learning strategy to alleviate this challenge. First, a small number of images are labelled by human annotators to train the first generation of the deep learning model (Gen0). Subsequently, the Gen0 model is employed to perform inference on additional images, producing preliminary labeling results, in which false labeling exists due to the limited accuracy of the Gen0 model. Human supervision is then introduced to improve the quality of annotation through corrections. These images with improved annotation are then added to the original dataset to retrain the model, producing the Gen1 model. This process is repeated until the desired accuracy level is achieved in the model. The iterative active learning strategy involving human-AI collaboration has proved effective as it greatly improves the efficiency of data annotation for training deep learning models for damage segmentation of concrete dam structures.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL MODELLING OF GEOGRID-REINFORCED AGGREGATE BEHAVIOR USING TWO DIFFERENT CONSTITUTIVE MODELS

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ABSTRACT

Geogrid placement in unbound aggregate layers provides lateral restraint as well as increased confinement to the aggregate assembly. Laboratory and field studies as well as numerical analyses have proven the confining effects achieved through geogrid reinforcement. Pavement designers often accommodate the beneficial effects of geogrid placement through improvement factors that modify certain mechanical properties of the entire layer. However, laboratory experiments such as pull-out tests have shown that geogrid-induced confinement only extends over a specific distance from the geogrid surface. The dimension of this ‘confined zone’ depends on individual and combined properties of the geogrid as well as the aggregate matrix. Therefore, modifying mechanical properties of the entire aggregate layer does not accurately represent the underlying mechanism of geogrid-aggregate interaction. Accurate prediction of stress distribution within the aggregate layer requires improved representation of the dimension and nature of this confined zone around the geogrid layer. Accordingly, there is a need for improved representation of geogrid-aggregate interaction through selection of appropriate constitutive material models. Lees (2019) developed a new constitutive material model called the TENSAR Stabilized Soil Model (TSSM) and implemented it into the PLAXIS 2D Finite-Element (FE)-based program. The TSSM is a linear-elastic, perfectly plastic material model developed to simulate the enhanced strength of geogrid-reinforced aggregate materials. In a recent study at Oklahoma State University, FE-based numerical analyses were carried out using the TSSM as well as the Hardening Soil Material Model (HSMM). The objective was to compare the effectiveness of the two constitutive models in simulating the stress-strain behavior of geogrid-reinforced aggregate specimens. Large-scale triaxial shear strength tests on unreinforced and geogrid-reinforced aggregate specimens were used for model calibration. The laboratory test data included geogrids with two different aperture shapes, placed at different positions within a cylindrical triaxial specimen. Stress-strain behavior of the geogrid was represented using both elastic and elasto-plastic material models. From the analysis, numerical models with both HSMM and TSSM could adequately predict the specimen failure stresses. Owing to the small strain levels induced in the geogrid during triaxial testing, both linear-elastic and elastoplastic material models predicted the specimen failure stresses with good accuracy. However, linear-elastic geogrid representation underestimated the constitutive model parameters within the confined zone. The TSSM overestimated the pre-failure stress-strain behavior, while HSMM could properly capture pre-failure as well as post-failure behavior.

Lees, A. S. (2019). The Tensar Stabilised Soil Model (TSSM) implemented into Plaxis finite element analysis software. Tensar International white paper.

VALIDATION OF TANK CAR DERAILMENT MODELS

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ABSTRACT

Derailment models are a valuable tool that can help further understand the behavior of tank cars during derailments. Empirical data on the impact forces that tank cars experience in derailments is not presently available. An increased understanding of those impact forces ultimately would lead to safer designs of tank cars. As such, there is a need to have accurate derailment finite element (FE) models that adequately simulate the performance of tank cars during such accidents. This work proposes validation techniques for high-fidelity FE models of train derailments. The validation techniques consist of assessing whether the model adequately captures the dynamic and kinematic behavior of a derailment and whether the resultant impact forces are reflective of an actual accident.

As such, this work proposes a newly developed derailment characterization system for quantitatively measuring the spatial disposition of a derailed consist. The system includes measures such as the consist and derailed position of tank cars, their location with respect to the derailment point of reference, and their orientation relative to the track centerline. This method can be used to compare and contrast actual and simulated derailments and evaluate the correspondence between the sizes and dispositions of actual and simulated pileups. Beyond these metrics, the number of cars derailed, and their ride-down velocities are also compared to validate the derailment dynamics comprehensively. The work then assesses whether FE models are adequately reproducing the impacts on tank cars in an accident by evaluating the location frequency of impacts and the corresponding distribution of impact areas. As an illustration, the proposed methods are used to validate the simulations of two major derailments in Cherry Valley, IL (2009) and Aliceville, AL (2013).

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN RELIABILITY AND RESILIENCE EVALUATION OF BRIDGE NETWORKS FOR PROACTIVE INFRASTRUCTURE MANAGEMENT

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ABSTRACT

Bridges are critical components of transportation infrastructure, serving as vital links for mobility and evacuation during and after hazard occurrences. Ensuring their reliability and safety is of paramount importance. Traditional reliability assessment methods for bridge networks rely on complex mathematical models, often resulting in time-consuming processes. This paper leverages the power of data-driven algorithms to streamline and enhance the reliability and resilience evaluation of this infrastructure. A novel data-driven method of approach is developed to quantify the resilience of a transportation network within a community to facilitate proactive maintenance and decision-making processes. The proposed methodology incorporates various data sources to develop a predictive model, including historical performance and inspection data, environmental factors, and structural characteristics. An ensemble of machine learning algorithms is used to train the predictive model and test its prediction accuracy to mitigate the risk of overfitting. Feature engineering techniques are employed to extract relevant information from the dataset, further enhancing the model's performance. Subsequently, the estimated reliability indices of bridges are used to perform network analysis and quantify the resilience of the network and its components by accounting for dependency between network components and the degree of centrality of each component for the mobility of the network. The proposed method is illustrated using heterogeneous real-world data for bridges and transportation infrastructure from a US community. The results show that the proposed approach possesses several features. Firstly, its capability to identify vulnerabilities in the transportation network helps inform decisions about prioritizing maintenance efforts during the life cycle of bridges (i.e., prior to extreme hazards) and prioritizing recovery following damaging events. Secondly, its flexibility to adapt to changing environmental conditions and evolving structural characteristics underscores its potential to be integrated into bridge management systems, providing a valuable tool for infrastructure stakeholders to make data-driven decisions and allocate resources efficiently.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC STRUCTURAL VULNERABILITY FRAMEWORK: HAZARD INTENSITY MEASURE AND FRAGILITY PARAMETERS CONCERNING THE RELIABILITY-BASED VULNERABILITY INDEX

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ABSTRACT

This research study proposes a comprehensive and implementable probabilistic damage assessment framework for highway structures, particularly bridges, which are highly vulnerable to damage and disruption during extreme events. The necessity of this research arises from the critical role that highway infrastructure plays in national economies and in ensuring public safety. Conventional methodologies to evaluate structural damage often need to be revisited to incorporate the excitation intensity and structural failure pattern uncertainties, leading to under-preparedness and inefficient allocation of resources for repair and maintenance. This research aims to bridge this gap by proposing a framework for calibrating intensity measures and fragility parameters for extreme events, including earthquakes, floods, and severe storms. The main contribution of this research lies in its innovative approach to probabilistic damage evaluation. By identifying the intensity of hazard effects, along with developing fragility functions of structural components and consequence formulas, the project aims to establish a new, probabilistic-based intensity measure specification. This involves an advanced structural damage assessment methodology and the creation of time-dependent fragility functions associated with introducing a reliability-based vulnerability index. Such a framework will enhance the accuracy of damage predictions and aid in effectively planning preventive and corrective measures. The benefits of this research are manifold. Firstly, it will significantly improve the safety and reliability of highway structures by enabling more precise and timely predictions of damage during extreme events. This leads to better-informed decision-making regarding design, maintenance, and emergency response strategies. Secondly, the framework will assist in conducting more accurate benefit-cost analyses, enabling policymakers and engineers to prioritize projects and allocate resources more efficiently. Furthermore, proposing a reliability-based vulnerability index will enhance risk management planning, identifying and fortifying the most vulnerable structures. Lastly, this framework will facilitate quicker and more effective post-event response and recovery in an extreme incident, thereby minimizing economic losses and disruption to transportation systems.

Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT UNCERTAINTY-INFORMED DAMAGE ASSESSMENT THROUGH MULTI-FIDELITY SIMULATION AND LATTICE ELEMENT METHOD

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ABSTRACT

The increased frequency of natural hazards and vulnerability of civil infrastructure has led to significant economic and societal impacts. The extent of such impacts calls for developing efficient approaches to examine the loss and devising strategies for mitigation and adaptation. These include quantifying the damage to structural and non-structural components at the scale of a community while considering the underlying uncertainties. Existing approaches for probabilistic loss assessment rely on Monte-Carlo simulations and thus use simplified assumptions for modeling structures to alleviate the computational cost associated with stochastic computations and community scale analysis. For instance, for such system-level analyses, buildings are modeled as multi-degree-of-freedom (MDOF) systems, and the details of structural elements, and the role of non-structural components are ignored [1]. Recently, the authors adapted the Lattice Element Method to develop an efficient tool for damage assessment that enables the simulation of buildings considering simultaneously structural and non-structural members [2]. We use LEM as our simulation tool to develop surrogate models for probabilistic damage assessment due to its robustness to discontinuity and damage, its computational efficiency, and versatility when simulating both structural members and non-structural components. Our approach for stochastic damage assessment relies on the use of a non-intrusive multi-fidelity approach based on the Kaczmarz updating scheme and polynomial chaos (PC) surrogates. We use the computational efficiency of the low-fidelity LEM models to build surrogates to identify and select the most informative samples for high-fidelity LEM simulations [3]. Our approach has shown significant computational efficiency by providing accurate results with a small number of high-fidelity LEM simulations.

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ENHANCING UNCERTAINTY QUANTIFICATION IN STRUCTURAL DAMAGE CLASSIFICATION USING WEIGHTED ENSEMBLES OF NEURAL NETWORKS

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ABSTRACT

The field of neural network-based predictive modeling is increasingly confronted with the challenge of accurately quantifying uncertainty, particularly in the context of out-of-distribution (OOD) data. This paper proposes a generalized weighted ensembling method designed to enhance both the accuracy and uncertainty measurement in neural networks, addressing the crucial aspect of disentanglement of epistemic and aleatoric uncertainties. While methods exist in the context of regression, the problem of classification, particularly relevant to the field of structural health monitoring (SHM), presents its own challenges in this regard.

The weighted ensembling approach proposed in this study offers a computationally efficient alternative to traditional ensemble fine-tuning methods, which are often resource-intensive. By weighting the contributions of individual models within an ensemble, our method seeks to improve the robustness and reliability of uncertainty estimates. This is particularly relevant in fields such as SHM, where models frequently encounter OOD data and require precise uncertainty quantification for decision-making.

We demonstrate the efficacy of our approach through applications on a synthetic dataset for a classification problem, as well as real-world SHM problems characterized by OOD challenges. The results indicate a significant enhancement in handling OOD data, with improvements in both predictive accuracy and the quality of uncertainty measurements. This research contributes to the broader understanding of uncertainty prediction in neural networks and offers a practical, scalable solution for a wide range of applications facing similar challenges.

Keywords: Uncertainty Quantification, Weighted Ensembling, Neural Networks, Out-of-Distribution Data, Epistemic Uncertainty, Aleatoric Uncertainty, Structural Health Monitoring.

Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SOFT-MAGNETIC SOFT-SOLIDS NONLINEAR SHELL MODEL

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ABSTRACT

We introduce a dimensionally reduced order model designed to accurately capture the nonlinear deformation of thin magnetoelastic shells with geometric precision. Our approach extends Kirchhoff-Love assumptions to encompass magnetic variables, establishing a two-dimensional theory through a meticulous variational approach. By prioritizing the general deformation map over mid-surface deformation, we enhance the accuracy of our model in describing nonlinear deformations. The conventional plane stress assumption is eschewed due to the impact of Maxwell stress in free-space, demanding meticulous treatment on both upper and lower shell surfaces. To address complexities stemming from boundary terms during the derivation of Euler-Lagrange governing equations, we employ a unique application of Green's theorem. To illustrate the model's capabilities, we analytically solve the governing equations for an infinite cylindrical magnetoelastic shell. This not only showcases the model's performance but also provides a tangible interpretation of new variables within our modified variational approach. This novel formulation for magnetoelastic shells emerges as an invaluable tool for the precise design of thin magneto-mechanically coupled devices.

Abhishek Ghosh, Andrew McBride, Zhaowei Liu, Luca Heltai, Paul Steinmann, Prashant Saxena, A fullycoupled nonlinear magnetoelastic thin shell formulation, arXiv:2308.12300, 2023

INTEGRATING ACCELERATION AND STRAIN MEASUREMENTS FOR STRUCTURAL DAMAGE DETECTION

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ABSTRACT

The structural integrity of civil and mechanical infrastructures is paramount for ensuring public safety and operational efficiency. This work presents a comprehensive methodology for structural damage detection by integrating the responses of a hysteretic model measured using accelerometers and strain gauges. Acceleration measurements are effective in capturing the overall vibrational characteristics while strain measurements offer insights into local deformations. However, the accelerometers are much more costly as compared to the strain gauges. Advantage of measuring strains at different locations aids in localizing damage or nonlinearities within the structure. The combined use of accelerometers and strain gauges not only enhances the sensitivity and reliability of the damage detection process but also introduces cost-effectiveness. This makes it accessible for a broader range of applications and also facilitates scalability for large-scale infrastructure. For the numerical illustration of the methodology, a cantilever column with some additional mass at its tip is discretized into finite elements by considering them as beam-type elements. Bouc-Wen hysteretic model is incorporated for the elements located near to the support in order to simulate the non-linearity of the column. The responses in terms of accelerations and strains are measured under base excitation. Additionally, this methodology is also implemented on a multi-story two-dimensional frame structure. The results show that the proposed data fusion methodology is effective in identifying the location and severity of damage in structures.

Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REVOLUTIONIZING THE ELECTRIC VEHICLE LANDSCAPE: ADDRESSING INDUSTRY CHALLENGES THROUGH ADVANCED COMPOSITE MATERIALS

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ABSTRACT

The electric vehicle (EV) industry has witnessed substantial growth in recent years, driven by a global push towards sustainable and eco-friendly transportation solutions. However, this burgeoning sector is not without its challenges, and one prominent hurdle lies in the materials used in EV manufacturing. This abstract explores the industry challenges associated with electric vehicles, with a specific focus on the utilization of composite materials to address these issues. One of the primary challenges in the EV industry is the weight of traditional materials used in vehicle manufacturing, such as steel and aluminum. The weight directly impacts the vehicle's efficiency and range, posing a significant obstacle to widespread EV adoption. Composite materials, which are lightweight and possess high strength-to-weight ratios, emerge as a viable solution to this challenge. By incorporating composites into EV designs, manufacturers can significantly reduce the overall weight of vehicles, thereby enhancing energy efficiency and extending the range. Another critical concern is the limited availability and high cost of certain rare earth metals used in electric vehicle batteries. This not only affects the cost of EV production but also raises concerns about the environmental and ethical implications of mining these materials. Composite materials provide an alternative avenue to mitigate reliance on rare earth metals. For instance, advancements in composite battery casings can offer lightweight and durable solutions without compromising performance. Moreover, the EV industry faces obstacles related to the recycling and disposal of batteries. Traditional battery materials pose environmental challenges, necessitating sustainable alternatives. Composites, being recyclable and environmentally friendly, present an opportunity to develop greener solutions for EV components. In conclusion, the challenges in the electric vehicle industry, including weight constraints, material scarcity, and environmental concerns, can be effectively addressed through the strategic use of composite materials. The adoption of composites in EV manufacturing holds promise for revolutionizing the industry, making electric vehicles more efficient, cost-effective, and environmentally sustainable. As technological advancements in composite materials continue, their integration into the EV sector is poised to play a pivotal role in shaping the future of sustainable transportation.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING-AUGMENTED PARAMETRICALLY UPSCALED DAMAGE MODEL FOR MICROSTRUCTURAL DAMAGE SENSING IN PIEZOELECTRIC COMPOSITES

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ABSTRACT

This work develops a digital twin for damage sensing in piezo-composite structures. It is based on a two-way (bottom-up and top-down) multiscale modeling framework coupling deformation, damage, and electric fields. The bottom-up or hierarchical multiscale modeling is achieved by developing a Parametrically Upscaled Coupled Constitutive Damage Model (PUCCDM). The PUCCDM is a thermodynamically consistent, reduced-order structural scale multi-physics constitutive damage model that has explicit dependence on its underlying material microstructure. The microstructure for these structures consists of unidirectional piezoelectric fibers distributed nonuniformly in a passive epoxy matrix that can undergo different damage mechanisms such as interfacial debonding, crack kinking, and propagation into the matrix etc. The PUCCDM incorporates the nonuniform microstructural morphology in its coefficients through Representative Aggregated Microstructural Parameters or RAMPs. Optimal expressions for RAMPs are determined through principal component analysis of the two-point correlation functions. The PUCCDM coefficients in terms of the RAMPs are determined using machine learning tools operating on data generated by micromechanical analysis. The developed PUCCDM is used for structural scale analysis of composite structures for understanding concurrent damage and failure at multiple scales. From analysis using PUCCDM it is observed that due to the electromechanical coupling in the piezocomposites, damage states in the structures are strongly correlated with its electrical response. Therefore, an electric signal can be used as a proxy indicator of the damage state. This leads to the top-down modeling framework that can quantitatively predict microstructural damage mechanisms from the measurement of a macroscopic electric signal and its corresponding RAMPs. An advanced machine learning model (ConvLSTM) based on the combination of a convolutional neural network (CNN) and a recurrent neural network (RNN) is developed for this purpose. This augmented neural network is advantageous over conventional machine learning models due to its capability to treat path-dependent nonlocal material response data. The trained machine learning model shows good damage prediction capabilities and good generalization characteristics for validation and test data. Thus, the digital twin model can be used as a quantitative global damage indicator in near-real time rather than a location-specific qualitative damage measure.

SCALABLE, TRANSPORTABLE THERMOCHEMICAL ENERGY STORAGE USING CEMENTITIOUS MATERIALS

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[1]Cache Energy

ABSTRACT

Energy storage based on reversible chemical reactions, termed thermochemical energy storage (TCES), has been proposed since the 1970s. TCES based on calcium oxide and hydroxide, where dehydration of Ca(OH)2 to CaO (lime) stores energy and the hydration of CaO to Ca(OH)2 releases the energy, is especially promising. The material is cheap at $100/ton, has high energy density at ~500 (W·h)/kg, the reaction is highly reversible, and the reaction temperatures of >550 oC can serve ~75% U.S industrial process heat demand. Additionally, the temperatures are high enough to drive efficient heat-to-power conversion cycles for electricity generation. However, commercialization of TCES has been hindered due to several material level challenges. One of the major challenges is the high volumetric change of >150% during charge/discharge process. This leads to lime pulverizing into fine powder which agglomerates and causes mass transfer limitations leading to capacity decay with cycling. In this work we explore various cement-based binders to provide strength and structural stability during high temperature cycling of lime. >1000 cycles with the full capacity retention was achieved. The cycling performance was highly sensitive to processing conditions such as water content, curing time and temperature. A minimum water content at ~40 wt% was found necessary and the cycling performance first improved and then worsened with increasing water content. In summary, the energy storage application requires research and development beyond the conventionally optimized cement properties.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-MATERIAL STRESS-CONSTRAINED TOPOLOGY OPTIMIZATION WITH UNIFIED YIELD CRITERION

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ABSTRACT

Multi-material topology optimization broadens the design landscape, enabling exploration of innovative designs with enhanced functionality. To harness the advantages of multi-material topology optimization while ensuring the optimized structures are functional when loaded, it's crucial for the formulation to consider material failure. Beyond the well-known challenges of single-material, stress-constrained topology optimization (such as the locality of stress constraints, singularity phenomenon, and stress constraint nonlinearity), a multi-material formulation must address various failure criteria, potentially having a different criterion for each candidate material. Here, we introduce a multi-material stress-constrained topology optimization formulation capable of handling distinct failure criteria with different yield strengths in a unified manner. Local stress constraints are applied at the centroid of each element, with one constraint per candidate material. The locally constrained problem is effectively solved using the augmented Lagrangian method. In this presentation, we provide details of the formulation and showcase several numerical examples to illustrate our ability to achieve multi-material designs. Additionally, we provide experimental validation of some of the designs obtained using our formulation.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MIXED-MODE COHESIVE ZONE MODEL FOR FRACTURE MODELING OF SELF-HEALING MATERIALS

Oliver Giraldo-Londoño[1], Daniel W. Spring[2] and Glaucio Paulino[3]*

[1]*University of Missouri*
[2]*The Equity Engineering Group, Inc.*
[3]*Princeton University*

ABSTRACT

Biological tissues such as skin or bones have the inherent ability to heal and regain their functionality. Inspired by this ability, scientists have developed synthetic self-healing materials which can sense and respond to damage to restore mechanical properties such as stiffness, strength, or fracture toughness. Although our ability to engineer and synthesize intrinsic self-healing materials has grown in recent years, our ability to model arbitrary fracture and healing events within a computational fracture mechanics framework is still in its infancy. A key challenge lies in the lack of constitutive models capable of capturing arbitrary healing cycles with varying healing times. In this work, we propose a mixed-mode cohesive zone model, inspired by the Park-Paulino-Roesler potential-based model, with the ability to handle arbitrary fracture and healing events. Our model, which is motivated by polymer chain dynamics models, evolves the maximum crack opening displacements in modes I and II using a reaction model during arbitrary rest periods. The maximum crack opening displacements are evolved only when the crack surfaces are in contact, and the rate of crack opening displacements is zero. This enables the model to capture arbitrary fracture and healing events seamlessly. In this presentation, we provide details of the formulation and present several numerical examples to elucidate its ability to model intrinsic self-healing materials.

A new horizon - Quantum computing and quantum materials (by invitation only)
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

QUANTUM COMPUTING FOR SIMULATING FLUID FLOW THROUGH FRACTURED MEDIA

John Golden[1] and Dan O'Malley[1]*

[1]Los Alamos National Laboratory

ABSTRACT

Simulating the flow of liquids, such as water or oil, through underground fracture networks poses significant challenges for traditional computing methods, particularly in accurately modeling critical aspects like percolation. Quantum computing offers a theoretical exponential speedup over classical methods by surpassing memory and processing constraints. However, many potential pitfalls exist in the acutal implementation of quantum algorithms in this case, such as the ill-conditioned nature of these systems and the need for efficient problem setup and information extraction. In this talk I will give an overview of these issues and the advancements we have made to overcome them, such as novel preconditioning techniques and measurement algorithms. These developments not only increase the feasibility of modeling complex subsurface flows with quantum computers, but also point the way towards applying quantum computing to solving other large-scale linear systems with real-world applications.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDITIVE MANUFACTURING OF PDMS-BLOWN FOAMS WITH TAILORABLE POROSITY

Melody Golobic[1], Larry Dugan[1], Taylor Bryson[1], Todd Weisgraber[1], Jeremy Armas[1], Eric Duoss[1], Tom Wilson[1] and Jeremy Lenhardt[1]*

[1]Lawrence Livermore National Laboratory

ABSTRACT

Hydrogen-blown polysiloxane foam chemistry can be combined with the Direct Ink Writing (DIW) technique to create architected foams with controllable, hierarchical porosity. Using a two-component foaming ink, the extent of foaming can be controlled by incorporating an active mixing printhead as part of the fabrication process. This allows for local control of the porosity within a given architecture, which in turn can be used to create materials with a unique material response. The details of the ink formulation, printing process, lattice design, and mechanical response of the architected materials will be outlined in this presentation. This research involves minimal post-processing compared to other techniques for creating porous structures, allows control of porosity on multiple length scales, and leverages the strengths of additive manufacturing to tune the energy absorption of architected lattices in a novel manner.

Reference: Golobic, A.M., Bryson, T.M., Weisgraber, T.H., Armas, J.A., Duoss, E.B., Wilson, T.S. and Lenhardt, J.M. (2023), Controlled In Situ Foaming for Mechanical Responsiveness of Architected Foams. Adv. Eng. Mater., 25: 2301335. https://doi.org/10.1002/adem.202301335

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSMENT OF THE PRINTABILITY OF ULTRA-HIGH-PERFORMANCE CONCRETE FOR DIFFERENT PRINTING SYSTEMS

Shady Gomaa[1], Ayesha Ahmed[1], Elmer Irizarry[1], Raul Marrero Rosa[1] and Gianluca Cusatis[1]*

[1]Northwestern University

ABSTRACT

A comprehensive understanding of the rheological characteristics of 3D printed concrete (3DPC) is crucial for the successful execution of the printing process. Previous literature suggests that the rheology of 3DPC is a material property. To further investigate this proposition, an experimental program was conducted using various printing systems on a nano-modified ultra-high-performance concrete (UHPC) mix. Nano clay was employed to modify the self-leveling UHPC mix, transforming it into a more viscous mixture with higher yield stress to improve layer stability post-extrusion. The experimental parameters included the extrusion system, nozzle outlet shape and direction, and material pumping. Two distinct extrusion systems, a piston-type, and an auger system were employed. Various nozzles, including circular and rectangular ones, were used. Material pumping to the extrusion system was found to play a crucial role in the stability of 3DPC layers. The results indicated that the printability of the UHPC mix is significantly influenced by the printing system, suggesting that concrete printability depends on the printing system rather than being an inherent material property, as suggested by other researchers. Furthermore, within the same printing system, changing the nozzle from a horizontal rectangular outlet to a circular vertical one had a noticeable impact on the stability of the printed layers. Additionally, the piston-type extrusion system produced non-printable results after pumping the mixture, attributed to the higher strain rates experienced by the material during the pumping process.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRESS FOCUSING IN SOFT LATTICES UNDERGOING EXTREME, TOPOLOGY-SWITCHING DEFORMATION

Caleb Widstrand[1], Joseph Labuz[1], Xiaoming Mao[2] and Stefano Gonella[1]*

[1]*University of Minnesota*
[2]*University of Michigan*

ABSTRACT

Recent developments in topological mechanics have demonstrated the ability of Maxwell lattices to focus stress along domain walls realized by stitching subdomains characterized by opposite polarization. The focusing ability provides a mechanism to protect the bulk of the lattice from stress concentration - and eventually onset and propagation of fracture - that can spontaneously occur at structural hot spots, such as defects, damage zones and cracks. An earlier study has revisited the problem for structural lattices featuring non-ideal hinges, as in the case of lattices obtained via machining, cutting or printing techniques. The study has shown that the focusing remains robust, albeit diluted in strength under these realistic conditions. While the problem of domain wall localization has been traditionally framed in the context of linear elasticity, here we deliberately extend the study to the realm of soft structures operating in the nonlinear regime and undergoing finite deformation. Through experiments performed on silicone rubber prototypes, we assess and quantify the robustness of the phenomenon against the macroscopic shape changes induced by large deformation, with special attention to deformation levels that alter the topology of the bulk, nominally lifting the topological protection. We report a remarkable persistence of the signature of polarization even deep into the nonlinear deformation regime. Additionally, we offer some insight in the geometric principles governing the persistence and loss of polarization under large deformation by invoking a simple analogy with the case of ideal lattices and identifying a simple kinematic parameter of the ideal lattice cell that correlates very precisely with the polarization observed in the entire structural lattice.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMPACT OF MISSING SOURCE AREAS AND VOLUMES ON BACK-CALCULATING REGIONAL EARTHQUAKE-INDUCED LANDSLIDES: A CASE STUDY OF THE 2020 MW 6.4 PUERTO RICO EARTHQUAKE

*Weibing Gong**[1]

[1]*Missouri University of Science and Technology*

ABSTRACT

In many existing landslide inventories, the total area of each landslide is mapped. However, the source area is often not delineated because the landslides may be too small to visually map the source area from optical imagery alone. This lack of source area information necessitates assuming a constant percentage of the total landslide area as the source area for back-calculation purposes. This study utilized the 2020 Mw 6.4 Puerto Rico earthquake event as a case study. In this event, only the total areas of landslides were mapped, with specific data on source areas and volumes lacking. To explore the effect of choosing a fixed percentage of total areas for approximating source areas on the back-calculation results, the entire possible range of ratios of source area to total area, namely 10%, 30%, and 50%, was adopted. The RESTAB-inversion algorithm, which typically requires information on landslide areas, volumes, and locations to invert regional earthquake-induced landslides by matching size and location, was employed. However, due to the absence of volume data for this event, the algorithm was constrained to using only the areas and locations of the landslides. The back-calculation results reveal that the shape, size, and location of the inverted modeled landslides visually match well with the mapped landslides across all assumed source-to-total area ratios. This indicates that using only the landslide area and location as constraints in the back-calculation process does not compromise the ability of the inverted modeled landslides to match the geometry and location of the mapped landslides. However, the absence of volume information introduced significant uncertainty into the back-calculated normal stress. In addition, the assumption of a constant source-to-total area ratio influenced the back-calculated strength parameters. This suggests that using a fixed percentage of the total area as the source area for an entire landslide inventory might be an oversimplification.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A THERMOREGULATING MODEL OF THE HUMAN EYE FOR LOCALIZED HYPOTHERMIA TREATMENT

Dipika Gongal[1], Craig Foster[1] and John Hetling[1]*

[1]University of Illinois Chicago

ABSTRACT

Ocular hyperthermia is a therapeutic technique that lowers the eye temperature to mitigate ischemic injury by reducing inflammation and preventing vision loss. An eye-cooling wearable thermoelectric device can provide precise and targeted temperature control during the treatment. The device consists of a cooling ring that is directly placed on the eye (sclera) and held in place by the eyelids. The cooling ring reduces the sclera surface temperature to 4°C, subsequently lowering the temperature of critical tissues at the posterior of the eye.

For the treatment to be effective, it must reduce the optic nerve head and retina tissue temperature, which are the most susceptible tissues to ischemic damage, to a therapeutic temperature range of approximately 34°C. To determine the efficacy of the cooling device a thermal analysis of the human eye is performed. A three-dimensional model of the human eye consisting of an eye globe and surrounding nerve tissue, muscle, and fat are considered for the analysis, following work in [1]. A thermoregulating non-equilibrium multiphase porous blood perfusion model is considered. The model incorporates the thermal exchange between ocular tissue and blood flowing into and out of the eye. Convection in the aqueous humor is also considered.

A transient analysis of the model shows that the optic nerve head and retina tissue temperature reaches the therapeutic temperature in approximately 10 minutes and reaches the steady-state within 60 minutes. At steady state, the optic nerve head and retina temperature are at 29.6 and 29.35, respectively, supporting the efficacy of the device.

[1] D. Gongal, S. Thakur, A. Panse, P. Shankarrao, J. A. Stark, J. R. Hetling, B. Ozgen, and C. D. Foster. “Thermal Finite Element Analysis of Localized Hypothermia Treatment of the Human Eye”. Medical Engineering and Physics, 111:103928 (2023) https://doi.org/10.1016/j.medengphy.2022.103928.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COASTAL NEXUS: INTERWEAVING SUSTAINABILITY DIMENSIONS IN INFRASTRUCTURE PERFORMANCE

*Catalina Gonzalez Duenas**[1]

[1]*George Mason University*

ABSTRACT

In the pursuit of global sustainability and resilience, the convergence of climate change, societal equity, and infrastructure resilience emerges as a critical focal point. The impacts of a changing climate, a growing population, economic shifts, and evolving social structures will escalate without action, particularly in highly vulnerable coastal areas. However, the substantial carbon footprint of the construction industry and the predominant emphasis on minimizing direct economic losses from natural disasters alone pose significant challenges. This underscores the urgent need for a shift towards sustainable practices, particularly vital in coastal regions susceptible to climate-induced hazards. This presentation aims to delve into the imperative of adopting a holistic approach to evaluate coastal infrastructure amidst the challenges posed by climate change. The objective is to introduce a framework that comprehensively assesses the multi-dimensional performance of coastal systems exposed to multi-hazard events within a changing climate context. The emphasis lies in reconciling conflicting objectives inherent in sustainable development—a vision that integrates environmental impact, societal value, and economic viability into infrastructure assessments.

Drawing from the Sustainable Development Goals as guiding principles, the discussion navigates towards establishing measurable performance benchmarks. These benchmarks not only inform the initial design but also gauge the ongoing performance of infrastructure systems over time. A critical aspect of this approach lies in leveraging diverse data sources—from satellite imagery and sensor networks to advanced numerical simulations—to enable robust decision-making in coastal infrastructure design and management. Furthermore, a discussion on the interconnectedness of individual structural performance within the larger infrastructure network underscores the significance of adopting a holistic systems approach. By examining these interdependencies, the talk concludes by highlighting the pivotal role of a systems thinking approach in addressing challenges and designing future coastal cities amidst the multifaceted challenges posed by climate-induced hazards.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF CIRCADIAN RHYTHM MODULATED BLOOD FLOW ON NANOPARTICLE BASED TARGETED DRUG DELIVERY IN VIRTUAL IN VIVO ARTERIAL GEOMETRIES

Shoaib Goraya[1], Shengzhe Ding[1], Mariam Arif[2], Hyunjoon Kong[1] and Arif Masud[1]*

[1]University of Illinois Urbana-Champaign
[2]Northwestern University

ABSTRACT

Delivery of drug using nanocarriers tethered with vasculature-targeting epitopes aims to maximize the therapeutic efficacy of the drug while minimizing the drug side effects. However, the retention of nanoparticles on the target vascular wall after the initial attachment remains to be further understood for rational nanocarrier design. Circadian rhythm also has implications for targeted drug delivery, particularly in the context of chronotherapy. Computational methods that are embedded with experimentally calibrated nanoparticle-endothelial cell adhesion models can provide insights into ligand-coated nanoparticle transport, distribution, and interactions with the vascular and interstitial environments in the context of chronotherapy.

In this paper we combine an advanced fluid dynamics modeling method that is based on convective transport of viscous incompressible shear-rate fluid (blood) coupled with an advection-diffusion equation to simulate the formation of drug concentration gradients in the flowing blood and buildup of concentration at the targeted site. The method is equipped with an experimentally calibrated nanoparticle-endothelial cell adhesion model that employs Robin boundary conditions to describe nanoparticle retention based on probability of adhesion, an asperity model accounting for surface roughness of endothelial cell layer, and a dispersion model based on Taylor-Aris expression to model shear induced diffusion in the boundary layer. Variational Multiscale (VMS) stabilization is done to accurately capture sharply varying concentration gradients in convection-dominated flows.

The method is first tested on engineered bifurcating arterial systems where impedance boundary conditions are applied at the outflow to account for the downstream resistance function at each outlet boundary in the arterial system. The method is then applied to an MRI-based arterial tree to highlight the capability for drug transport, adhesion, and retention at multiple sites in virtual in vivo models, thereby providing a virtual platform for exploiting circadian rhythm modulated blood flow, for minimizing the in vivo experimentation.

Computational geomechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MICROSTRUCTURE DESCRIPTORS FOR PREDICTIVE HOMOGENIZATION

Anna Gorgogianni[1] and Chloé Arson[1]*

[1]Cornell University

ABSTRACT

Homogenization theory explicitly accounts for the influence of material microstructure on the macroscopic mechanical response. A homogenization model idealizes a generally complex microstructure, by accounting for a few physical features, usually identifiable by experimental imaging, such as cracks in solids, grains and pores in granular media, crystals in polycrystalline materials. With the goal of increasing the predictability of homogenization models, the present study aims to inform these models by determining the microstructure features that govern the mechanical behavior of a given heterogeneous medium.

This goal is achieved by analyzing the error propagation from a given microstructure feature to the effective stiffness tensor. More specifically, a set of realistic three-dimensional microstructures is firstly created using a generative adversarial neural network (GANN), that takes as input two-dimensional images from experimental micrographs and produces heterogeneous material volumes, statistically indistinguishable from the experimental training data. Numerical homogenization using the finite element (FE) method is performed on this set of reference microstructures, yielding the ground-truth probability distributions of the effective stiffness tensor components.

New sets of microstructures are then generated with a descriptor-based microstructure reconstruction method. The new microstructures are created such that they are identical to the reference ones in all features but one. Each distinct set of microstructures introduces a user-defined error in one selected microstructure descriptor at a time, e.g. volume fraction, n-point correlation. The distributions of effective stiffness tensor components for the sets of modified microstructures are computed by FE analysis, and compared with the corresponding ground-truth distributions. The governing microstructure descriptors are identified as those resulting in the most pronounced error propagation in the effective stiffness tensor.

This study considers the fundamental case of isotropic linear elasticity. Future work will investigate how the microstructure features that dominate the mechanical response vary with the applied loading for the case of irreversible, path-dependent material behavior. One could expect that the governing microstructure features change as localization or phase transition phenomena occur. This can inform the representation of the microstructure used in homogenization models, resulting in an adaptive homogenization scheme, that can predict mechanical response in the presence of multi-scale phenomena.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONVERGENCE OF LES AND FULL-SCALE MEASUREMENTS FOR PEAK WIND LOAD PREDICTIONS

Jack Hochschild[1] *and Catherine Gorlé*[*1]

[1]*Stanford University*

ABSTRACT

This talk will present an investigation of the potential of large-eddy simulations (LESs) and full-scale measurements towards analyzing peak wind pressure loads on high rise-buildings. Previously, the emphasis has been on validation of LES predicted wind pressures against wind tunnel measurements. These validation exercises demonstrated that LES can accurately predict the complex bluff body flow physics, but they also revealed the non-negligible influence of uncertainty in the wind tunnel boundary layer on the predicted wind pressures. Hence, the current focus is on validation against full-scale pressure measurements. Measurements were performed on two high-rise buildings using a novel wireless pressure sensing network and LESs of the flow around those buildings and the surrounding urban environment were performed. Comparison of the measurement and simulation results largely confirms the findings of previous wind tunnel validation studies, but also reveals the additional challenges introduced by the natural variability in the full-scale wind flow. The results demonstrate the benefits of methodological convergence for the analysis of wind effects on buildings, where the LES results can provide detailed insights into the flow physics that govern extreme suction events, while the full-scale measurements provide a valuable reference data set to validate and complement the simulation results.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF STRUCTURAL BATTERY COMPOSITES USING A VIRTUAL TEMPERATURE CONSTRAINT TO ENSURE BI-CONTINUOUS MATERIAL DISTRIBUTIONS

Jonathan Gorman[1], Reza Pejman[1] and Ahmad Najafi[1]*

[1]Drexel University

ABSTRACT

Structural Battery Composites (SBC) are a novel class of multifunctional materials that simultaneously act as a lithium-ion battery and support mechanical loads. By incorporating SBCs into structural components of a design, extensive weight savings can be observed – for example in electric vehicles. Previous studies have found optimized designs of SBCs; however, the solutions obtained in these works do not possess bi-continuous material distributions [1]. For example, islands of Structural Battery Electrolyte (SBE) with high ionic conductivity exist within the structural phase's domain. This is problematic as it makes passing current between the battery electrodes difficult.

The purpose of this study is to deploy a virtual temperature constraint in the design framework that will help to ensure bi-continuous material distributions in the SBC layout. Virtual temperature constraints have previously been used to prevent enclosed voids or islands of solid material in structural designs [2]. In this methodology, the materials will be assigned a fictitious thermal conductivity – high conductivity for the SBE and low conductivity for the structural phase. Additionally, the SBE phase will act as an artificial source of heat generation. Dirichlet Boundary Conditions with zero temperature are applied to the battery electrodes' locations. By constraining the p-norm of the virtual temperature field, an effective current path within the battery can be generated.

This design framework is multi-objective and uses the normalized-normal-constraint method. The objective functions considered in this study are maximizing the ionic conductivity and minimizing stiffness of the SBC. To enhance the computational efficiency of the design framework, a fully analytical sensitivity analysis is derived and implemented using the adjoint method. Additionally, the framework uses the portable extendable toolkit for scientific computing and message passing interface to further reduce computational time. Several computational problems are solved to demonstrate the versatility of this new design methodology.

[1] Pejman, Reza, and Ahmad Raeisi Najafi. "Multiphysics topology optimization of a multifunctional structural battery composite." Structural and Multidisciplinary Optimization 66.3 (2023): 46.

[2] Swartz, Kenneth E., et al. "Manufacturing and stiffness constraints for topology optimized periodic structures." Structural and Multidisciplinary Optimization 65.4 (2022): 129.

Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INDUSTRY-ACADEMIA RESEARCH COLLABORATION: OPPORTUNITIES AND MECHANISMS

Kundan Goswami[1] and Eric Sammarco[1]*

[1]Protection Engineering Consultants, LLC

ABSTRACT

This talk aims to highlight influential factors and strategic pathways that are expected to enhance industry-academia research collaborations. With an intent to foster connections between fundamental research in academia and market oriented applied research in industry, the talk will focus on two aspects: (i) broad technical challenges and associated research opportunities that might be of interest to the EMI/PMC 2024 conference audience and (ii) various mechanisms that are available for industry-academia collaborative research funding.

The “technical challenges and opportunities” segment of our talk will present an overview of a few practical problems of interest. The problems are drawn from a pool of recent Small Business Innovation Research (SBIR) and/or Small Business Technology Transfer (STTR) opportunities advertised by federal agencies, such as, National Science Foundation (NSF), Department of Energy (DOE), Department of Transportation (DOT), etc. The “collaboration mechanism” segment of our talk will provide in-depth information on various research funding schemes, such as, SBIR, STTR, and Grant Opportunities for Academic Liaison with Industry (GOALI), that are focused on stimulating collaboration between Institutions of Higher Education (IHEs) and industry.

The talk is expected to develop awareness on market-need-oriented and technically stimulating research opportunities, as well as associated funding mechanisms. The talk promises to motivate both academic and industry researchers to more actively seek organic partnerships and viable funding mechanisms that offer the potential to culminate into future joint research funding applications and ultimately provide a bigger push toward advancing the state-of-the-art in engineering mechanics.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Toward data-driven approaches for uncertainty quantification and propagation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NETWORK VULNERABILITY ASSESSMENT: CRITICAL COMPONENT IDENTIFICATION

Kundan Goswami[1], Michael Shields[23] and Eric Sammarco[1]*

[1]*Protection Engineering Consultants, LLC*
[2]*Johns Hopkins University*
[3]*UQuant, Inc.*

ABSTRACT

Network systems are ubiquitous. Network theory can be used to model various infrastructure systems such as utility grids, telecommunications and cyber systems, transportation routes, water/oil distribution pipelines, etc., and non-infrastructure systems such as social media, advertising, and other web-based systems. These infrastructure and non-infrastructure network systems are critical to a nation’s economic growth and must remain functional in the aftermath of a natural or man-made disaster. Hence, resilience of these network systems is of utmost importance from an economic and national security standpoint. An important step towards resiliency assessment of a network system is vulnerability assessment, which can be achieved by considering an appropriate mathematical model representing the network topology and identifying the critical components, i.e., the nodes and edges that significantly influence the integrity and performance of the network. Network vulnerability analysis is a combinatorial problem involving evaluation of a large number of node and/or edge failure scenarios, and therefore, is computationally expensive for large networks with thousands of nodes and edges. The computational complexity of the problem limits the number of scenarios that can be explored thereby leading to increased risk of network failure. This poses a major concern for various network system operators from reliability and resiliency standpoint and must be addressed.

Our current research focuses on development of computationally efficient algorithms for effective identification of components (i.e., nodes and edges) that are most critical to overall functionality of a network. The algorithms aim at ranking network components based on the effect of removal of a component or a collection of components on the network performance. The talk will present a few selected algorithms and highlight their effectiveness using various random graph models that are representative of infrastructure and non-infrastructure network topology, e.g., Erdős-Rényi (binomial) graphs, Power Law graphs, Watts-Strogatz graphs, Barabási–Albert graphs, etc.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMODYNAMIC BASIS FOR WATER POTENTIAL CONCEPT

Chao Zhang[1]*, Lingyun Gou**[1]*, Shaojie Hu*[1] *and Ning Lu*[2]

[1]*Hunan University*
[2]*Colorado School of Mines*

ABSTRACT

In the mid-20th century, harnessing of thermodynamics in describing water movement in soil, viz the concept of water potential, marks the emergence of modern soil physics, unsaturated soil mechanics, and vadose zone hydrology. Yet to date, a seamless linkage between thermodynamics and water potential is still missing, leading to several long-lasting dilemmas regarding soil properties, for example, abnormal soil water density, peculiar film water viscosity and relative permittivity, pore water pressure, and water freezing temperature depression. Here, a thermodynamic framework is established by synthesizing recent advancements in soil-water interaction. The classical thermodynamic concepts are revisited, highlighting the difference between macroscopic systems commonly treated in conventional theories and the intermolecular scale system subject to external fields. Soil water is conceived as an intermolecular scale open thermodynamic system subject to external fields of gravity, osmosis, and adsorption. The formulated thermodynamic framework is verified by reducing to the conventional definition of matric potential and a recently proposed unitary definition. The accuracy of the framework is further justified in terms of mechanical equilibrium criteria. The framework predicts the existence of spatially varied pore water pressure in soil pores and can serve as the theoretical basis for reconciling the physical origin of abnormal soil behavior such as water density, film water viscosity, relative permittivity, and negative or positive pore water pressure.

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FULLY PARAMETRIC ESTIMATION METHOD FOR THE HYBRID SWITCHING DIFFUSION MODEL

Zheming Gou[1], Roger Ghanem[1] and Sergey Lototsky[1]*

[1]University of Southern California

ABSTRACT

The Hybrid Switching Diffusion model (HSD) is introduced as a powerful probabilistic framework capable of encoding micro-to-macro path-wise relationships, enabling efficient generation of sample paths with prescribed statistics for high-fidelity simulations. However, current non-parametric estimation methods suffer from data-intensive requirements and susceptibility to overfitting. In this paper, we introduce a comprehensive full parametric estimation algorithm based on the Expectation Maximization (EM) algorithm, approximating drift and diffusion functions using polynomials as well as modeling transition probability dependencies through polynomial representations, thus transforming the problem into the estimation of polynomial coefficients. It not only provides a more robust estimation framework but also reduces the data requirements for accurate characterization, making it easily extendable to multi-variate scenarios. Numerical examples are provided to demonstrate the performance of the estimation algorithm. We also apply it to finite element simulation data of composites and polycrystalline. The estimated hidden states match well with micro-scale behaviors, and sample paths generated by the new model are more physics-consistent. The proposed method presents a significant advancement in the probabilistic characterization of multi-scale simulations, offering a more efficient and adaptable method for uncovering hidden dynamics within complex physical systems.

IMPACT ANALYSIS OF MASONRY TOWERS: A COMPARATIVE STUDY

Lauren Goyette[1] and Branko Glisic[1]*

[1]Princeton University

ABSTRACT

Embarking on a journey through time and stone, this study explores the dynamics of masonry towers from a selected population of castles subjected to cannonball impact load using finite element modeling and historical evidence. Motivated by the need to comprehensively understand historic tower dynamics under simulated loads, this study seeks to provide insights into tower performances and vulnerabilities and inform strategies for their conservation. By considering shape, construction materials, structural elements, and historic evidence, this work aims to discover how historic design choices influence the structures' response to simulated impacts. Its principal contributions include a historical analysis of the selected cases, creation of a 3D numerical model, case-specific impact analyses, and a comparative analysis across the selected population.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FULL AGGREGATE REPLACEMENT BY CRUSHED SEASHELL WASTES IN ENVIRONMENTAL-FRIENDLY CONCRETE: A LOCAL AND CIRCULAR INDUSTRIAL CASE-STUDY AT THE DUNE OF PILAT CONSTRUCTION SITE IN FRANCE

David Grégoire[1], Tematuanui a Tehei Hantz[1], Benjamin Niez[1] and Olivier Nouailletas[1]*

[1]Universite de Pau et des Pays de l'Adour

ABSTRACT

Concrete is one of the most used materials in the world and its demand continues to grow. However, the processes of obtaining raw materials for concrete (cement production and aggregate extraction) are associated with many environmental impacts such as climate change or resource depletion.

To design more sustainable concrete, we may minimize the quantity of classical cement used in the formulation, replace it by clinker-free cement or reuse industrial waste as extracted aggregate replacement. This study focuses on the use of crushed oyster seashell wastes as full aggregate replacement for more environmental-friendly concrete in the context of the renovation of the Dune of Pilat site in France. The Dune of Pilat is the tallest sand dune in Europe and it is located in the Nouvelle-Aquitaine region in the Arcachon Bay area, 60 km southwest of Bordeaux along France's Atlantic coastline. With more than two million visitors per year, the Dune of Pilat is a famous tourist destination and the reception area has been fully renovated in 2023 with a strong will from local authorities to promote environmental-friendly materials within a local and circular economy.

In 2020, almost 83 percent of EU oyster production took place in France and Nouvelle-Aquitaine is the first oyster farming region in France which generates an important amount of seashell wastes (Europe contributes hundreds of thousands of tonnes annually to discarded seashells).

Within this context, innovative formulation of environmental-friendly concrete has been proposed with 100% replacement rate of aggregate to maximize the valorization of local seashell wastes.

First, the granular skeleton grading has been optimized to minimize the final intergranular porosity coming from the non-spherical shape and the high elongation of the seashell aggregates. Given the coastal context, CEMIII cement has been chosen but the formulation has been adapted to minimize the cement quantity (300kg/m3) while maintaining the performance corresponding to the targeted applications (pedestrian path and steps). Finally, the formulation was implemented in an industrial context, casted on site and the evolution of the mechanical properties in environmental conditions was carried out.

The methodology can be reproduced in any region that produces seashell waste and it is currently implemented in French Polynesia within the context of pearl oyster seashell waste reuse.

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Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CITY-SCALE WIND-INDUCED BUILDING MOTION SIMULATION BASED ON OBLIQUE PHOTOGRAPHY AND TIME HISTORY ANALYSIS

Ning Zhang[1]*, Zhen Xu*[1]*, Ahsan Kareem*[2] *and Donglian Gu**[1]

[1]*University of Science and Technology Beijing*
[2]*University of Notre Dame*

ABSTRACT

High-rise buildings inherently exhibit heightened vulnerability to wind loads, posing a significant structural integrity and stability risk. This study investigates the safety considerations associated with tall buildings by analyzing the characteristics of wind fields and aerodynamic responses within the intricate context of urban building clusters. The research adopts a novel approach that integrates oblique photography data with computational fluid dynamics (CFD). Details of this work are as follows.

(1) To tackle the complexity of building models, this study introduces a voxel-based method to convert point cloud data to CFD models. Initially, lightweight and single-object processing is performed for the point cloud data obtained from oblique photography. Then, the processed data are voxelated with the mesh reconstruction, forming the basis for constructing a CFD model.

(2) The large eddy simulation results of the established CFD model are compared with those derived from the high-resolution model (i.e., the model obtained from the oblique photography without the voxelization processing) and the 2.5-dimensional simplified model (i.e., the model established by stretching the planar polygon of the building along the height direction), indicating that the wind pressure coefficient of the voxelated CFD model exhibits encouraging consistency with that of the high-resolution model.

(3) Finally, the city-scale wind-induced building motion is simulated using the voxelated CFD model and time history analysis. This study employs multi-degree-of-freedom models to simulate the dynamic response of building clusters. Besides, several specific landmark buildings are selected as case studies to scrutinize their response distribution characteristics. The results provide a comprehensive analysis of the aerodynamic behavior of urban building clusters, contributing valuable insights into the wind-induced dynamic response of similar building complexes.

In summary, this work leverages oblique photography data for wind field simulation of building complexes and adopts city-scale time history analysis to predict wind-induced building motion. The whole simulation is implemented based on the open-source CFD platform OpenFOAM and newly coded structural dynamic analysis algorithms. The findings serve as a valuable reference for incorporating oblique photography data in wind field simulations and understanding the aerodynamic responses of building clusters at a city scale.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIMULTANEOUS TOPOLOGY OPTIMIZATION OF MATERIALS AND STRUCTURES

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ABSTRACT

Simultaneously optimizing structure topology and local material properties has been of interest to the design and topology optimization communities for some time. Taking various forms and names, including multi-scale topology optimization and free material optimization, and varying levels of mathematical rigor, the topic remains an open challenge in terms of creating meaningful, fully-optimized structures. In addition to simplifying assumptions that underlie modeling of such structures, manufacturability also remains a challenge, as manufacturing constraints and details are often neglected. This talk will discuss recent advances to address these challenges in the context of fiber-based composites and multi-material additive manufacturing. We will discuss various technologies, including automated fiber placement technologies, and new topology optimization methods for leveraging these technologies. Multiple structural design examples will be presented, focusing on optimization for mechanical properties.

Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ROLE OF PARAMETRIC RISK TRANSFER IN BRIDGING THE PROTECTION GAP IN INFRASTRUCTURE RISK MANAGEMENT

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ABSTRACT

The complex interdependent nature of an infrastructure network (i.e., consisting of transportation, water, power and telecommunication networks) exacerbates the uncertainties in the quantification of the socio-economic consequences that a catastrophic event may have on the affected community. The focus of the scientific community is often oriented to the risk reduction component of risk management, which typically involves investments in a more resilient infrastructure planning and design, or, in case of an existing infrastructure network, in its retrofitting, expansion and enhancement.

This contribution focuses on a complementary component of risk management, namely the transfer of the monetary losses via financial tools such as (re)insurance mechanisms. Calculating the right balance between retention (the amount of loss the insured must incur before the insurance coverage takes effect) and (re)insurance is a common task in risk management. This decision process is facilitated by the use of catastrophe models that, for a given portfolio, are able to estimate the frequency of expected direct losses. However, impacts to an infrastructure network disperse the consequences of a disrupting event and cause sizable “indirect” losses, such as business interruption and suspension losses, or increased supply chain and supply chain interruption costs, which often are challenging to understand, quantify, and hence model. Models of indirect losses are still in their infancy, which hampers the widespread adoption of traditional (re)insurance products, and widens the protection gap between economic and insured losses.

We discuss the role of parametric risk transfer as a key tool to bridge the protection gap in the infrastructure management sector, focusing on its ability to respond quickly to a variety of events that can affect the infrastructure network. Parametric insurance is a type of risk transfer mechanism that pays based on the characteristics (parameters) of an event, independently from the actual losses sustained. Payouts are fast, transparent, and versatile, as parametric insurance does not require a loss adjustment process. Instead, payments are based on measurements publicly provided by a reputable third party (like NOAA, NASA or the USGS), and –notably– they are not tied to any specific asset, allowing the recoveries to be used as needed to support a wide range of impacts.

Small scale phenomena in sustainable & complex materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMO-NANOMECHANICS OF HEAT TRANSFER NANOFLUIDS FOR SUSTAINABLE DEVELOPMENT

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ABSTRACT

Nanofluids have the potential to play a significant role in sustainable development through their ability to improve thermal conductivity and heat transfer efficiency. This ability can lead to a reduction in energy consumption and greenhouse gas emissions in various industries such as power generation, automotive, and HVAC systems. In this study, thermo-rheological performance of heat transfer nanofluids as the function of nanoparticle type and concentration was studied. Additionally, stability, which is one of the main parameters which influences the long-term application of nanofluids, was studied using particle size analysis and zeta potential measurements. The results show that the nanofluids exhibit good stability when treated with a surfactant. In terms of rheology, nanofluids exhibited a higher viscosity than the corresponding base fluids. This increase is due to the presence of the nanoparticles which leads to improved lubrication and reduced wear and tear in machinery and equipment. Thermal analysis revealed that these heat transfer nanofluids have higher thermal conductivity than the corresponding base fluids, which can be attributed to the large surface area of the nanoparticles and increased Brownian motion. It was concluded that Brownian motion of the nanoparticles is the main nano-mechanism for improved performance leading to an increase in the heat transfer coefficient. This increase is attributed to the enhancement of the convective heat transfer caused by the increased turbulence in the fluid by the nanoparticles. Additionally, this enhanced thermal conductivity of the nanofluids allows for a reduction in the temperature difference between the heat source and the heat sink, leading to a more efficient heat transfer process for sustainable development. Overall, the thermo-nanomechanics of nanofluids can play a key role in sustainable development by improving energy efficiency and reducing greenhouse gas emissions through proper selection of type and dosage of nanoparticles for customized applications.

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN NETWORKS DRIVEN LIFE-CYCLE SEISMIC RESILIENCE OF HIGHWAY BRIDGES

Hongyuan Guo[1], Ruiwei Feng[1] and You Dong[1]*

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ABSTRACT

Abstract: The comprehensive seismic assessment of highway bridges in marine environments plays a crucial role in guiding long-term operations, maintenance, and repair decisions. However, existing life-cycle seismic assessment methods predominantly focus on the structural performance under constant environmental conditions during the design stage, neglecting the effects of realistic time-variant exposure conditions and inspection results during the service life on bridge seismic resilience assessment. Thus, this study introduces a novel life-cycle resilience assessment framework by using the Mixed Bayesian Network (MBN), including three modules: durability assessment, capacity analysis, and life-cycle seismic resilience. This study encompasses time-variant marine environmental parameters and a two-dimensional chloride transport model to perform durability evaluation. Meanwhile, a representative prestressed concrete highway bridge will be selected for illustrative purposes. Using 500 samples of representative environmental parameters, a parametric numerical model was established on the OpenSees platform. Nonlinear time-history analysis should be conducted on each bridge model using real ground motion records to determine seismic demands, capacity, and system fragility changes over the service life. Subsequently, an MBN is established to predict the life-cycle seismic resilience of the bridges. Finally, supposing different inspection results (the widths of concrete surface cracks and half-cell potential measurement), the effects of inspection results on the probabilistic characteristics of seismic resilience over time will be thoroughly discussed.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRADED PROTECTION ANALYSIS OF SEA-CROSSING BRIDGES FOR SHIP COLLISION

Jian Guo[1], Zheng Wang[1] and Yuhao Cui[1]*

[1]Southwest Jiaotong University

ABSTRACT

Abstract: During the operation of a sea-crossing bridge, unexpected situations such as ship collisions may occur, which affects the safety and reliability of the bridge structure. Therefore, installing a large number of collision prevention devices in the waters near the navigational spans has become one of the optimal choices for existing bridges. However, it is not appropriate to only consider the impact force received by the bridge and ignore the weakening effect of protective devices when evaluating the impact of ship collisions. Based on this, this paper establishes a two-degree-of-freedom simplified dynamic model considering collision prevention devices and proposes a graded protection criterion for ship-bridge collisions. In order to verify the rationality and applicability of the proposed criterion in engineering, a finite element model of a three span simply supported beam bridge including the designed graded protection device, was established with a large-scale sea-crossing bridge in the East China Sea as the engineering background. The results show that the external steel structure and internal elastic body of the anti-collision device can absorb about 76% of the impact energy, and the remaining energy is absorbed by various parts of the bridge structure. In addition, when using ships with different initial velocities for collision, it was found that this graded protection has a significant buffering and energy absorption effect on collisions of different intensities. This study helps to reduce the risk of catastrophic accidents caused by ship collisions. More detailed, the dynamic model proposed can accurately calculate the ship collision force on the bridge after installing prevention devices, and the graded protection criterion provide a reference for the design of existing collision prevention measures.

Keywords: Sea-crossing bridge; Ship-bridge collision; Graded protection; Anti-collision device

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACCURATE ESTIMATE OF THE WIND PROFILE IN THE PLANETARY BOUNDARY LAYER BY COMBINING PHYSICAL AND RANDOM FORECAST APPROACHES

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ABSTRACT

The accurate estimate of wind profile in the planetary boundary layer has great implications for weather, climate and renewable energy. Nevertheless, the air flow above the heterogeneous underlying surface generally does not obey the Monin-Obukhov similarity theory, owing to the ubiquitous turbulence. This tends to result in an unreliable estimate of wind profile from the conventional extrapolation methods and needs a novel algorithm. To this end, we propose a novel method that combines the power law method (PLM) with the random forest (RF) algorithm (termed as Phy-RF), based on two kinds of high-resolution measurements of wind from radiosonde and radar wind profiler stations, which are widely distributed across China. The underlying principle is to treat the wind profile as a power law distribution in the vertical direction, in which the power law exponent (α) is determined by the Phy-RF model. First, the Phy-RF model is constructed based on the atmosphere sounding data at 119 radiosonde (RS) stations across China and in conjunction with other data such as surface wind speed, land cover type, surface roughness, friction velocity, geographical location, and meteorological parameters from June 2020 to May 2021. Afterwards, the performance of the Phy-RF, PLM and RF methods over China are evaluated by comparing them with RS observations. Overall, the wind speed at 100 m of the Phy-RF model exhibits high consistency with RS measurements, with a correlation coefficient (R) of 0.93 and a root mean squared error (RMSE) of 0.92 m s−1. By contrast, the R and RMSE of wind speed results from PLM (RF) method are 0.87 (0.91) and 1.37 (1.04) m s−1, respectively. This indicates that the estimates from the Phy-RF method are much closer to observations than those from the PLM and RF methods. Moreover, the RMSE of the wind profiles estimated by the Phy-RF model is relatively larger at highlands, while is small in plains. The result indicates that the performance of the Phy-RF model is affected by the terrain factor. Finally, the Phy-RF model is applied to three atmospheric radiation measurement sites for independent validation, and the wind profiles estimated by the Phy-RF model are found consistent with the Doppler Lidar observations. This confirms that the Phy-RF model has good applicability. These findings have great implications for the weather, climate and renewable energy.

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TROPICAL CYCLONE SCENARIOS FOR RISK-INFORMED RESILIENCE ASSESSMENT OF COASTAL COMMUNITIES UNDER A CHANGING CLIMATE

Yue Dong[1], Yanlin Guo[1], Norberto Nadal-Caraballo[2], Madison Yawn[2], Bruce Ellingwood[1], Hussam Mahmoud[1] and Luke Aucoin[2]*

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ABSTRACT

Coupled wind and storm surge hazards under tropical cyclones (TC) pose a significant threat to coastal communities in the Southeast and Gulf regions of the United States, a threat that is being amplified by sea level rise and a changing climate. Wind and storm surge from TCs are spatially and temporally non-homogeneous and the demands they place on a community are highly non-uniform and uncertain. An assessment of community damage and resilience requires that these variabilities in the wind field and storm surge and in the civil infrastructure within the community be modeled accurately at similar scales. A scenario-based approach, which captures this spatial and temporal variabilities and uncertainties in the presence of a changing climate, personalizes the hazard and risk for a decision-maker who is familiar with past TC events and facilitates communicating consequences of the hazard to the public and mobilizing financing for risk mitigation.

In this presentation, we introduce a de-aggregation approach to identify TC scenarios that are dominant contributors to community risk, considering the joint distribution of wind and storm surge accompanied by SLR in a changing climate. The track and intensity of scenario TCs are simulated using a statistical model, while the corresponding storm surge is estimated with machine learning-based prediction models that have been trained using data from extensive hydrodynamic analyses. Non-stationarities of TC events brought on by climate change is considered in a life-cycle analysis of civil infrastructure. TC scenarios identified through the de-aggregation are further investigated to determine damage and economic losses to a coastal community and to initiate recovery analysis of engineered facilities. Infrastructure damage and recovery patterns within the community are depicted, enabling an improved framework for long-term community resilience planning and risk-informed decision-making. This framework is illustrated for a key Gulf Coast industrial community patterned after Mobile, AL.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ARCHITECTED FOAMS FOR COMPACT AND LIGHTWEIGHT CUSHIONING

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ABSTRACT

Cushioning materials used in packaging, helmet liners, and recoil pads absorb kinetic energy while minimizing peak acceleration caused by blunt impacts. Architected lattices, in comparison to stochastic elastomeric foams, can be designed to exhibit higher energy absorption per unit volume of the material, enabling the creation of compact-sized energy-absorbing pads. However, due to their higher modulus, the pads need to be made much thicker to minimize the acceleration imparted on the object being protected. In this study, we establish requirements for the constitutive stress-strain response, density-dependent scaling of modulus, and relative density to simultaneously minimize both the volume and mass of the cushioning pad while keeping peak acceleration and maximum compression strain below desirable limits. Utilizing architected vertically aligned carbon nanotube foams with a mesoscale architecture of closely packed cylinders, we demonstrate tunability in density-dependent scaling of the properties as well as the constitutive stress-strain response as functions of varying architecture. This tunability allows for achieving low relative density for a targeted stress-strain response and density-dependent scaling to enable a lightweight and compact cushioning design.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE MATERIALS MODELING AND OPTIMIZATION BY BRIDGING SCALES USING A DEEP CONVOLUTIONAL NETWORK

Ashwini Gupta[1] and Lori Graham-Brady[1]*

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ABSTRACT

Designing heterogeneous materials with enhanced properties requires efficient modeling of material behavior and properties across multiple scales. However, performing a full-scale finite element (FE) discretization of the multiscale resolution is often impractical due to high computational cost. Furthermore, scale separation using an FE-squared based multi-level discretization approach heavily depends on the choice of micro-scale boundary conditions and introduces errors along element boundaries. To address these challenges, we propose a novel deep learning based scheme for bridging scales in multiscale mechanics modeling. The proposed U-Net deep learning model based on a convolutional neural network (CNN) is trained on a small dataset of composite microstructures and the corresponding linear elastic stress tensor fields. This deep learning model learns underlying physics from the micro-scale simulations and transfers this knowledge to perform multiscale analysis of the macroscopic boundary value problem at a resolution of the micro-scale. The proposed approach is applied to a variety of macro-structure shapes, loadings, and boundary conditions and the results are compared with the conventional multiscale modeling approaches. We show applications of this approach in uncertainty quantification, multiscale design, and microstructure-resolved optimization.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CORTICAL BONE-INSPIRED TOUGH TUBULAR ARCHITECTED CEMENTITIOUS MATERIALS

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ABSTRACT

Natural materials demonstrate an exceptional combination of competing mechanical properties, fracture toughness and strength, by assembling modest constituents into complex arrangements and hierarchical architectures that trigger clever toughening mechanisms [1]. Cortical bone is a tough shell of the human femur bone and is composed of elliptical tube-like osteons embedded in the organic matrix that is surrounded by weak interfaces known as cement lines [2]. The cement lines provide a preferable micro-structural path for crack growth, hence triggering in-plane crack deflection around elliptical osteons due to cement line-crack interaction [3]. In this research, inspired by cortical bone's toughening mechanisms, the tubular architected cement-based materials are engineered into the design and fabrication by employing a hybrid 3D-printing and casting method as well as a layer-wise additive manufacturing process. The statistical mechanics approach is also employed to deepen the understanding of seemingly periodic tubular voids by translating periodicity to translational and orientational order parameters.

Using experimental, theoretical, and numerical (phase-field) approaches, we demonstrate that tubular architected cementitious material exhibits significantly improved fracture toughness and a non-brittle fracture response compared to conventional monolithic brittle counterparts without sacrificing flexural strength. This improvement is enabled by crack-tube interaction which leads to a new stepwise cracking toughening mechanism, from which a non-brittle fracture can emerge. The tubular geometry, tube size and shape, compete to alter stress intensity factor which can be engineered to enable stepwise cracking. The stepwise cracking then promotes rising R-curves vs. the flat brittle response of solid (without the tubes) counterparts. These tubular architected materials composed of brittle components can be exploited to promote a global non-brittle behavior and enhance damage tolerance by pinning the crack to the tubes. The findings can be extended to quasi-brittle materials such as mortar and concrete, contributing a strategy for enhancing the fracture toughness of concrete materials while reducing material usage through the deliberate design of intentional defects.

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Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DRIVING INTO THE FUTURE: EXPLORING THE EFFICACY OF ARTIFICIAL INTELLIGENCE IN TRAFFIC MONITORING AND CAPACITY ASSESSMENT FOR MORELIA CITY, MEXICO

José A. Guzmán-Torres[1], Francisco J. Domínguez-Mota[1], Gerardo Tinoco-Guerrero[1] and Elia M. Alonso-Guzmán[1]*

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ABSTRACT

Nowadays, it is possible to notice that as urban centers continue to grow, the complexity of managing the traffic flow increases. This phenomenon might be observed in rapidly expanding cities like Morelia, Michoacán, and México. This presentation explores a cutting-edge approach to traffic analysis by employing artificial intelligence (AI) models for vehicle counting and capacity estimation. The study aims to revolutionize how we understand and manage urban mobility by contrasting the effectiveness of AI methods against traditional approaches.

The city of Morelia, known for its rich cultural heritage and historical significance, faces the challenges of modern urbanization, including escalating traffic congestion. Traditional traffic analysis methods often fail to provide real-time, accurate, and scalable data for effective urban planning and road structural design. In response, our research focuses on implementing AI models trained to analyze traffic patterns, count vehicles, and estimate road capacity in Morelia City.

This work begins by providing an overview of Morelia's existing traffic management methods, emphasizing their limitations and the increasing demand for innovative solutions. Consequently, we integrate an AI approach, detailing the development and deployment of machine learning models tailored to the unique traffic dynamics of the city. These models leverage advanced computer vision techniques to count vehicles and estimate road capacity autonomously.

The comparative analysis forms a crucial aspect of our study, wherein we compare the outcomes of AI-based traffic analysis with results obtained through traditional methods. This includes manual counting, pneumatic detectors, and other conventional approaches widely used in traffic studies. Through comprehensive data comparisons, we aim to showcase the advantages of AI models in terms of accuracy, efficiency, and scalability. Furthermore, the research discusses the practical implications of our findings for urban planners, transportation authorities, and policymakers in Morelia. The potential impact of integrating AI-based traffic analysis on enhancing traffic management strategies, optimizing infrastructure development, and ultimately improving the quality of life for residents will be highlighted.

In conclusion, this research presents a forward-looking perspective on the role of AI in transforming urban mobility. Our research aims to contribute valuable insights for creating smarter, more efficient, and sustainable urban transportation systems by bridging the gap between technology and traditional methodologies.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

USING MACHINE LEARNING TO IMPROVE THE QUALITY OF GRADIENT-BASED TOPOLOGY-OPTIMIZED DESIGNS

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ABSTRACT

Topology optimization presents a new opportunity for engineers to discover unique structural design solutions that can outperform conventional approaches. This design paradigm can therefore leverage the rapidly developing computation and manufacturing possibilities. In accordance with significant advances in machine learning methodology, including deep learning, a great amount of studies has been dedicated to enabling rapid and effective optimization by applying machine learning to topology optimization. Notable categories for such applications include acceleration of iteration, non-iterative optimization, generative design, and post-processing (Shin et al., 2023).

This work uses machine learning to improve the quality of the design by automatic setting of the input parameters or incorporating human preferences. This framework is based on traditional density-based topology optimization (Andreassen et al., 2010), using SIMP and method of moving asymptotes (MMA) (Svanberg, 1987) as the gradient-based optimizer.

Machine learning is wrapped around this standard optimization framework. For the case of automatic parameter tuning, surrogate optimization is used to tune the hyperparameter of the topology optimization algorithm. This is done by formulating an outer optimization problem where the hyperparameters are the design variables, and the objective considers not only the objective function of the normal topology optimization problem (such as compliance minimization), but also the quality of the design. For the case of incorporating human preferences, machine learning is used to inform the user the best location of a topology to gain performance improvements. This metric can be either structural (buckling load factor), or aesthetical. The work is based on previously developed Human-Informed Topology Optimization (HiTop) that allows the user to interactively highlight region of interest for the algorithm to adjust accordingly (Ha & Carstensen, 2022). The efficiency of the new framework is discussed, as well as its performance on various benchmark problems.

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Using pavement mechanics to develop pavement materials with less environmental impact
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INNOVATIVE MATERIAL CHARACTERIZATION APPROACHES FOR ENHANCED RECYCLING AGENT OPTIMIZATION: A COMPREHENSIVE STUDY ON BIO-BASED AND PETROLEUM-BASED AGENTS IN ASPHALTIC MATERIALS

Hamzeh Haghshenas[1], Adrian Andriescu[1], Raj Dongre[1], Varun Veginati[1], David Mensching[2] and Jack Youtcheff[2]*

[1]Genex Systems/Turner Fairbank Highway Research Center
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ABSTRACT

This study explores innovative methods for characterizing materials, with a specific focus on optimizing recycling agents (RAs) for asphalt mixtures. The research delves into both bio-based and petroleum-based RAs, employing advanced rheological and failure-based approaches. The investigation reveals that the RA optimization based on the high-end Performance Grade (PG) successfully recovers crucial asphalt binder characteristics, establishing its efficacy in the optimization process. Simultaneously, surrogate methods like the Asphalt Binder Quality Test and Glover-Rowe approaches show promise, providing viable avenues for estimating optimal RA dosages. A noteworthy finding from the Double Edge Notched Tension approach identifies a cost-effective dosage, warranting further scrutiny through in-situ experiments. In the next phase of this research, the selected dosages based on the high-end PG is introduced to asphalt mixtures with 40% reclaimed asphalt pavement (RAP), aiming to achieve performance comparable to mixtures with a lower RAP content (i.e., 20%). Evaluation through testing methodologies, including the Hamburg Wheel Tracking Test for rutting and moisture damage characterization, and the Indirect Tensile Asphalt Cracking Test for cracking characterization, indicates improved cracking resistance without compromising rutting and moisture resistance properties. However, after subjecting all mixtures to the different long-term aging conditions, a noticeable reduction in cracking resistance is observed. The comparison between aging protocols highlights varied performance among the mixtures, emphasizing the need for further research in selecting appropriate aging protocols. In conclusion, this study not only provides valuable insights into innovative methods for material characterization but also offers a pathway to increase the use of recycled materials without sacrificing performance in asphalt mixtures. This study highlights the ongoing effort to find eco-friendly solutions in construction materials. It helps us better understand how recycling agents, asphalt mixtures, and long-term aging interact, contributing to a more sustainable approach in construction.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONVOLUTIONAL NEURAL NETWORK FOR ULTRASONIC IMAGING OF ARBITRARY FLUID-FILLED INCLUSIONS IN SOLID

Jinho Hahn[1], Salma Abdelgawad[1], Boyoung Kim[1] and Chanseok Jeong[1]*

[1]Central Michigan University

ABSTRACT

We present a data-informed convolutional neural network (CNN) to detect fluid-filled inclusions within a two-dimensional (2D) solid domain using wave responses measured at surficial sensors. ANSYS Mechanical is utilized to simulate the propagation of elastic waves in the solid containing internal fluid inclusions. The training dataset comprises input-layer features (measured wave responses) and output-layer features (a contour map representing solid or fluid cells in the domain). The CNN is trained to classify each cell as solid or fluid based on the measured wave responses at sensors.

The methodology focuses on utilizing elastic waves within a plain strain domain where a fixed boundary condition is applied at the bottom boundary. A CNN architecture shows efficiency in capturing complex patterns of the relation between wave measurement and element types. Hyperparameter optimization, facilitated by KerasTuner, enhances CNN performance by minimizing loss and preventing overfitting or underfitting during training. This study’s numerical experiments reveal the validity and adaptability of the proposed methodology in identifying fluid-filled inclusions within a solid domain. Specifically, this study presents numerical experiments with respect to various parameters, including the number of sensors, the amount of training data, and frequency, and provides a comprehensive analysis of their effect on the outcomes.

Advances in vibration and structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PASSIVE ELIMINATION OF VORTEX-INDUCED VIBRATIONS FOR OFFSHORE STRUCTURES USING PIPE-IN-PIPE MODEL

Ussama Ali[1] *and Muhammad Hajj**[1]

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ABSTRACT

This study addresses the critical challenge of vortex-induced vibrations (VIV) in offshore structures influenced by fluid flow, where VIV resulting from vortex shedding poses a significant risk of structural damage and failure. To address this issue, this work focuses on innovative passive control method aimed at mitigating VIV effects without relying on active control or additional energy sources. Specifically targeting monopiles, foundational elements for offshore structures, the study explores the effectiveness of the pipe-in-pipe (PIP) model, building upon the original work proposed by Nikoo et al. [1, 2]. In our investigation, the passive PIP model is advanced to analyze system performance across a range of reduced velocities (Ur = 2 to 12) at a fixed Reynolds number (Re = 100). This numerical study investigates the VIV of the PIP system using a two-way coupled fluid-structure interaction (FSI). The comprehensive results encompassing lift, drag, amplitude, and frequency of vibrations, along with an examination of flow characteristics, contribute to a thorough understanding of the system's behavior. Numerical findings demonstrate the significant reduction of VIV in the PIP system, affirming the effectiveness of the passive control PIP method. This work contributes valuable insights into the complex interaction of fluid dynamics and structural dynamics in offshore engineering, providing a foundation for the design of resilient systems.

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Mechanics and modeling of pavement structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECTS OF CONFINEMENT CONDITION ON DUCTILITY OF ASPHALT BINDERS

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ABSTRACT

Since the 1950s, the poker chip geometry has been widely used to study the fracture mechanisms in soft solids. Recent advances in development of this test as a practical evaluation tool for asphalt binders have led to implementation by practitioners and stakeholders within the industry. However, the test still can be further optimized to develop a better fundamental understanding of the underlying mechanisms which affect engineering properties of pavement materials. This research seeks to use both modeling tools and experimental techniques to examine the effect of the confinement condition within this geometry on the ductility of asphalt binders. Specifically, the triaxial state of stress is used to better represent the realistic condition which binder experiences when confined between two aggregates. In this study, the film thickness is manipulated to examine the effect of confining stresses on the nonlinear viscoelastic properties and damage propagation within the binder. This is paired with traditional micromechanical models to better understand how the confinement comes into play when damage occurs, as well as represented through computational models. Finally, a brief evaluation on the effect of large particles such as waste plastic or crumb rubber is shown to examine the effect these inclusions have at different film thicknesses.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNDERSTANDING HISTORIC WOOD STRUCTURES AND HOW TO ASSESS THEM

Steven Hall[1]*

[1]Simpson Gumpertz & Heger

ABSTRACT

The majority of historic buildings in the United States include a substantial amount of wood structure, especially in floors and roofs. However, early American wood milling and construction methods such as deep-notched joints and cored timber columns are not practiced today. In addition, changes to building code criteria for a naturally occurring material make it difficult to estimate appropriate allowable stresses for wood members of varying vintage on a given historic project. Add in the potential for concealed decay, and the analysis of historic wood structures becomes a challenge for even seasoned engineers.

The process of assessing the historic wood structure begins with a visual survey to understand structural load paths and to identify potential locations of decay or distress. Once the engineer understands how the structure is intended to support the loads, he/she can employ a testing and analysis “toolkit” to determine the strength of the wood and further understand the extent of any decay that needs to be addressed. These toolkit items include sampling and microscopic analysis to determine the wood species, in-situ visual grading of adequately exposed wood members that comprise the structure, in-situ moisture content testing, and resistance-drill probing of the wood.

Finally, when modern building codes and reference standards do not adequately address historic wood erection methods and geometry, finite-element modeling can provide insight into the behavior of the structure under loading. At times, engineering analysis may identify portions of the structure that have insufficient capacity to support the code required design loads. In these instances, the engineer needs to develop details that strengthen the existing structure while maintaining as much of the historical appearance as possible. In this presentation we will describe typical historic wood structures, discuss testing procedures and analysis methods, and introduce strengthening concepts.

ACTIVE SEISMIC MONITORING OF DRY AND SATURATED ROCK FRACTURES

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ABSTRACT

Assessment of rock mass stability and the prediction of impending failure depend on the ability to monitor and identify data signatures of changes in the mechanical behavior of rock fractures. A number of methods have been used to detect slip along rock fractures, with acoustic emission and active seismic monitoring being the two most commonly used approaches. Here, we explore the effect of water saturation on the onset of slip and the geophysical response of rock fractures undergoing shear.

Laboratory direct shear tests were conducted on a frictional discontinuity between a two-block rock specimen with dimensions of 152.4 mm x 127.0 mm x 50.8 mm. A frictional discontinuity was created by inducing a tensile fracture on the specimen through a modified Brazilian test. Indiana limestone and Sierra White granite specimens were sheared under an effective normal stress of 2 MPa. The tests were performed under dry and saturated conditions in a custom-built pressure chamber. Saturation was achieved through vacuum first, followed by an increase in the chamber pressure. Full saturation was attained when no further increase of the B-value was observed with an increase in the chamber pressure. In all the tests, during shear, compressional (P) and shear (S) waves were transmitted across the fractured specimens.

For dry conditions, all transmitted and converted waves showed a distinct maximum in wave amplitude prior to failure, followed by a decrease in wave amplitude with additional shear displacement. The peak amplitude resulted from local damage of the fracture in the field of view of the probing transducer, and thus, can be considered a seismic precursor to the shear failure of the discontinuity. For saturated conditions, precursors in the form of maxima of the transmitted S-wave amplitudes were also observed. However, the P-waves and the converted waves showed a continuous reduction in amplitude. Further scrutiny observed that a noticeable change in the reduction rate of the P-wave amplitudes coincided with the peak in the S-wave amplitudes, suggesting that, even though the sensitivity of P-waves to detect damage was significantly reduced by fluid saturation, it was still sufficient to detect precursory events. It is also interesting to note that precursors occurred first close to the application of the shear load, followed by other precursors along the discontinuity with further shear, thus suggesting that slip does not coincide along a rock fracture but that it initiates locally and then propagates across the discontinuity until failure.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATISTICAL FRACTOGRAPHIC ANALYSIS OF STEEL DUCTILE FRACTURE USING COMPUTER VISION TECHNIQUES

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ABSTRACT

Scanning electron microscopes (SEMs) yield fractographs, which provide direct visual evidence of the key mechanisms that contribute to steel fracture. However, manual analysis of SEM images can be laborious, intricate and error prone. This study presents a new technique for automatic segmentation and feature analysis of fractographs using computer vision. The SEM images were randomly sampled from microvoid coalescence and shear lip regions of the fracture surfaces of tensile notched bars tested under ultra-low cycle fatigue (ULCF) loading schemes. Statistical analysis was then conducted to identify the geometric characteristics of the fractographic features and describe their probabilistic distributions. The findings obtained from this type of analysis offer valuable insights for formulating refined empirical void growth models.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECONSTRUCTION OF MULTI-PHASE CEMENT PASTE VIRTUAL SPECIMENS USING DEEP LEARNING

Sung-Wook Hong[1], Se-Yun Kim[1], Donghwi Eum[1] and Tong-Seok Han[1]*

[1]Yonsei University

ABSTRACT

The time and effort consuming real experiments for evaluating properties of cementitious materials such as cement paste can be supplemented by simulations using virtual specimens. To accomplish this task, the uncertainties of cement paste microstructures should be properly characterized and be reproduced in reconstructed virtual specimens for simulation. However, reconstruction of multi-phase cement paste microstructures is not trivial, and conventional methods such as stochastic optimization [1] is impractical to generate such virtual specimens. In this study, a framework for reconstruction of 3D multi-phase cement paste microstructures using deep learning is proposed. In particular, the generative adversarial networks (GAN) approach [2] is extended to reconstruct virtual specimens based on real microstructures obtained using micro-CT measurements. The reconstructed multi-phase microstructures are found to have the statistically the same microstructural characteristics as the real multi-phase microstructures. The stiffness and tensile strength of microstructures from real specimens and reconstructed specimens are evaluated using simulations. It is confirmed that the reconstructed microstructures can reproduce the similar property distribution as the real microstructures. With further development, the proposed framework should be able to accelerate the innovative new material development and the performance evaluation of existing cementitious materials.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMMUNITY RESILIENCE ANALYSIS UNDER SEISMIC HAZARDS USING AGENT-BASED MODELING

Xu Han[1] and Maria Koliou[1]*

[1]Texas A&M University

ABSTRACT

Community resilience is a highly multi-disciplinary research topic as the recovery of a community hinges upon the restoration of the functionality of multiple systems in the community, such as residential, business, and lifeline infrastructure, among others. How to model the interactions among different systems represents a significant challenge to the researchers interested in conducting community resilience analysis. Of all the approaches for conducting community resilience analysis, the agent-based modeling approach is promising in addressing this challenge. By generating different types of agents to represent various entities of the community systems, the recovery process of each system as well as their interactions can be simulated in a high resolution. This study employs the agent-based modeling approach in simulating the recovery process of a community under seismic hazards. Using the generated agent-based model (ABM), the influence of the location of the epicenter and the depth of the earthquake on community resilience is investigated. In addition, the effect of structural retrofit actions for the residential buildings on the resilience of households is also studied. Retrofit strategies considered involve retrofitting different types of residential buildings and at various retrofit levels.

Small scale phenomena in sustainable & complex materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISSOLUTION KINETICS OF CALCIUM HYDROXIDE

Yoonjung Han[1], Natasha V. D. Levy[1], Umme Zakira[1], Jonathan Lapeyre[2], Mine Ucak-Astarlioglu[3], Jedadiah F. Burroughs[3] and Jeffrey W. Bullard[1]*

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[2]Pacific Northwest National Laboratory
[3]U.S. Army Engineer Research and Development Center

ABSTRACT

Portlandite (Ca(OH)2) is the most prevalent cement hydration phase, constituting about 27% of the hydrated cement paste. It is prominent near aggregates or fiber within the microstructure, often called the interfacial transition zone (ITZ). Significant research has been conducted on the dissolution of portlandite, as it can readily transform into pozzolanic Calcium Silicate Hydrate (C-S-H) or Calcite (CaCO3), of which transformations have opposite effects on concrete's strength and durability. However, most of the studies are more focused on simulations than experimental studies due to the difficulties involved in experimentation. This research is the second part of a study on the pozzolanic reaction rate during the initial hydration process, focusing on the experimental study. Following previous studies on the dissolution rate of silica fumes, this research investigates the dissolution rate of portlandite. We measured the dissolution rate of portlandite in pure water using a batch reactor test with a conductivity meter, similar to previous research. We aim to use a rate equation to improve cement hydration models by accounting for pozzolanic components in modern concrete mixtures, including ultrahigh-performance concrete. Ultimately, this will enable us to include pozzolanic reactions in the THAMES model of 3D cement hydration and microstructure development.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATIVE MULTI-HAZARD FRAGILITY ASSESSMENT: ADVANCING COMMUNITY RESILIENCE THROUGH CUMULATIVE DAMAGE MODELLING

Mojtaba Harati[1] and John van de Lindt[1]*

[1]Colorado State University

ABSTRACT

This study introduces a robust methodology for developing multi-hazard fragility models, leveraging multi-distributed and parallel processing to perform comprehensive two-phase nonlinear analyses, which includes managing uncertainties across multiple layers. The goal is to create an extensive fragility portfolio for reinforced concrete (RC) and light-frame wood structures, acknowledging the sequential damage due to earthquakes followed by tsunamis. Integrating the behavior of long-duration earthquakes, as documented in the Cascadia subduction zone-focused M9 Project, refines the earthquake-tsunami fragility surfaces to better quantify their impact on structural integrity. Moreover, this portfolio of multivariate fragilities provides better input for community-level resilience analysis that accounts for the cumulative and compound effects of such natural hazard events. The findings demonstrate the method's efficacy in highlighting the initial damage from the source earthquake and the subsequent amplification of damage due to tsunamis, thereby stressing the importance of a prepared infrastructure. This advanced analytical toolset focuses on structural typology and can equip communities with the means to improve resilience by enabling a comprehensive multi-hazard evaluation of economic losses and spatial damage, thereby streamlining the decision-making process for enhanced community resilience.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENABLING HIGH-DIMENSIONAL WAVE PHYSICS-INFORMED LEARNING

Joel Harley[1], Amanda Beck[1], Woohyun Eum[1], Michael MacIssac[1], Matthew Stormant[1], Charlie Tran[1] and Ghatu Subhash[1]*

[1]University of Florida

ABSTRACT

Wavefield data analytics can be used to identify and understand the complex, heterogeneous, and anisotropic characteristics of a material system. These characterizations can be used in nondestructive evaluation, structural health monitoring, vibration control, metamaterials, materials discovery, and other areas. However, a data processing framework for the entirety of wavefield dataset generally requires an analysis in at least three dimensions: two dimensions of space and one dimension of time. The introduction of additional dimensions, such as an angular dimension in the case of anisotropic wave propagation, can further complicate such data. Alternatively, such analysis may also include additional dimensions representing unknown parameters, such as wave speed, that can be leveraged to estimate or learn the distribution of those parameters across space and time. Given the computational challenges of processing such high-dimensional data, most analysis techniques limit themselves to analyzing one or two of the dimensions at any given time.

This work presents an unsupervised physics-informed machine learning framework designed to analyze full high-dimensional datasets to extract the parameters and individual wave modes from the measured wavefields. We demonstrate how to formulate high-dimensional physics-informed optimization frameworks using tensor mathematics. We then show that the computational burden of applying these optimization frameworks can be significantly reduced through the use of spectral decompositions. Given this decomposed representation, we demonstrate how the physics-informed optimization can be efficiently solved.

We demonstrate the results of this approach using simulated and experimental data for guided Lamb waves in metallic plates. We focus on datasets with spatially heterogeneous characteristics. We show that the physics-informed framework can learn the wave velocities that define this spatial heterogeneity and extract the individual modes within multiple heterogeneous regions across the plate. The results are achieved without the need for supercomputers, and we show that the computational cost scales linearly with the number of elements in the data.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZATION AND HYBRID TESTING OF A ROLLING ISOLATION SYSTEM WITH RESPONSE-BASED ADAPTIVE BEHAVIOR

Miguel Payan[1], Menziwokuhle Thwala[1], Esteban Villalobos Vega[1] and P. Scott Harvey[2]*

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ABSTRACT

Isolation systems can perform well when their displacement demands do not reach their displacement capacities. When the isolator’s displacement capacity is insufficient to meet the demands of a disturbance, the performance of the isolator is diminished because of impacts, giving rise to high acceleration responses in isolated objects. Isolation systems can be designed to reduce the likelihood of impacts by reducing displacement demands and/or by increasing displacement capacity. The former objective may be realized by adhering elastomeric materials to the rolling surfaces or balls, at the expense of increasing total accelerations. The latter objective may be realized by increasing the size of bearing components (e.g., bowls/balls), but doing so is cost prohibitive because the price of components increases exponentially with size and may be infeasible due to seismic gap limitations. Seismic isolation systems should be designed to meet both objectives over a wide range of disturbance intensities, requiring response-based adaptive behavior. In this paper, a double rolling isolation system (dRIS) is proposed, which exhibits response-based adaptation through engineered nonlinearities in the constituent isolator components. The rolling surfaces geometries (profiles) are tailored to stage the displacement first in the lower system at low loads and then in the upper system at higher loads. The lower system utilizes steel balls, which exhibit light rolling resistance, whereas the upper system utilizes rubber balls, which have higher rolling resistance. Therefore, light damping is realized at small displacements (i.e., under service level excitations where acceleration reduction is important), and higher damping at large displacements (i.e., under design-basis or higher excitations where displacement reduction is critical). A small-scale prototype of the dRIS was fabricated and tested. The rolling surfaces were 3D printed, allowing for highly customizable profiles. Prescribed displacement tests were performed on the subsystems and combined system to characterize the system’s gravitational restoring force and damping. Then, hybrid tests are conducted to incorporate the influence of flexible equipment mounted atop the isolation system.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UAV-BASED MONITORING SYSTEM FOR WATER PONDING DETECTION AND VOLUME ESTIMATION ON MUNICIPAL SOLID WASTE LANDFILLS

Syed Zohaib Hassan[1], Peng "Patrick" Sun[1], Poyu Zhang[1], Jiannan Chen[1] and Debra Reinhart[1]*

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ABSTRACT

Regular monitoring of municipal solid waste (MSW) landfills is essential to ensure proper operations and compliance with environmental protection regulations. These requirements include periodic inspections of landfill covers (e.g., water ponding issues, gas emission hotspots, vegetation), estimating waste volume, and quantifying waste settlement. The current methods employed by the landfill industry to meet these demands are time-consuming and labor-intensive, and have limited spatial coverage. Therefore, this study evaluated a UAV-based monitoring system using multi-modal sensor fusion to facilitate waste management and operations. Over several months, long-term monitored data have been gathered using UAV-based remote sensing (e.g., LiDAR, photogrammetry) on both active and closed landfills. A novel water ponding index (PI) is designed to identify both potential and existing ponding regions on the landfills. Additionally, the collected data are analyzed to estimate the monthly changes in volume and to measure waste settlement . The proposed method is validated by ground truthing (e.g., manual surveying, surface emission monitoring). The match between the experimental results and ground truth detections demonstrates a satisfactory performance. The UAV-based sensing system proves to be an efficient automated method for ponding detection and volume/settlement estimation on MSW landfills.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INHOMOGENEOUS VISCOELASTIC SHEAR PROPERTIES OF HUMAN AND PORCINE CORNEA

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ABSTRACT

The cornea, the transparent tissue in the front of the eye, is responsible for the majority refractive power of the eye and the protection of its delicate inner contents against external forces. The cornea is constantly subjected to shear forces caused by blinking and eye rubbing. The corneal shear properties are due to its extracellular matrix, which is a composite structure composed of collagen fibrils and proteoglycans. In diseased states such as keratoconus, the composition and microstructure of corneal extracellular matrix are compromised. The corneal crosslinking (CXL) is a treatment procedure that creates additional crosslinks inside corneal extracellular matrix in order to enhance its structural integrity. The strengthening effects of the CXL procedure has primarily been characterized in tension and less is known for its effect on corneal shear properties. In this work, we characterized corneal inhomogeneous shear properties before and after the CXL treatment. The composition and microstructure of corneal extracellular matrix is significantly different in anterior and posterior region; thus, we used a DSAEK system to excise anterior and posterior corneal flaps. Both human and porcine samples were used in order to determine the differences and similarities between their biomechanical properties. The porcine cornea, compared to human donor samples, is more easily accessible and more commonly used in biomechanical measurement studies. The standard photosensitizer solution, 0.1% riboflavin monophosphate and 20% dextran, and 30-minute-long UVA light irradiation with 3 mW/cm2 intensity and 370 nm wavelength were used to crosslink corneal disks. The corneal disks were placed between the lower and upper plates of a DHR-2 rheometer and their dynamic shear properties were determined. The experimental measurements confirmed that the shear stiffness of anterior part of the cornea is significantly stiffer than its posterior region. Furthermore, the shear modulus of human anterior corneal flaps was found to be markedly stiffer than porcine flaps. The CXL treatment enhanced significantly the shear stiffness of anterior flaps in both porcine and human samples. The measured shear properties were hydration dependent, i.e. with increasing the hydration, a softer shear property was measured. In summary, this study determined similarities and disparities of inhomogeneous viscoelastic shear properties of human and porcine corneas before and after CXL therapy.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEW METHOD FOR THREE-DIMENSIONAL PORE NETWORK IDENTIFICATION OF CLAYS USING FIB-SEM IMAGING

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ABSTRACT

For several decades researchers have highlighted the complexity of mechanical behavior of fine reactive particulate media such as clays, the point being especially on how to relate the microstructure properties to mechanical loading (see for instance the works of Collins & McGown, 1974; Hicher et al., 2000; Sivakumar et al., 2002; Hattab & Fleureau, 2011). Several techniques have been developed aiming to analyze the micro level behavior of clays through observations using various experimental approaches in post-mortem and/or in-situ conditions. For this purpose, scanning electron microscopy (SEM) is a common investigative technique generally used to support the mercury intrusion porosimetry (MIP) technique. These studies have made important contributions permitting to comprehend the clay micromechanics, however observation methods by SEM are based on plane surface observations, which represents a strong limitation. This limitation makes it necessary a need of obligatory extensions from 2D approach to 3D analysis of the results.

This paper proposes new an original technique aiming to go further towards the 3D characterization in clay microstructure. To achieve this, an approach using FIB-SEM imaging coupled with image processing techniques has been developed allowing to generate a three-dimensional microstructure from digital 3D reconstruction.(Ding et al., 2023).

The tests using FIB-SEM technique were carried out on remolded saturated clay samples submitted to one-dimensional compression. Particular emphasis was placed on how to rebuild, with sufficient accuracy, the pore network of an observed micro-volume. Then, pores properties were investigated in terms of pore size distribution, morphology, and spatial orientations. Finally, Pore size distribution deduced from FIB-SEM was then superimposed to mercury intrusion porosimetry results allowing more discussions around the FIB-SEM technique efficiency.

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BOTH SPECIMEN SIZE AND SAMPLE SIZE MATTER FOR MATERIAL CERTIFICATION

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ABSTRACT

We explore the significance of number of samples and their size on the credibility of product certification. We deduce that both have important implications on the statistical confidence in the certification process. We adopt the formalism of "design allowable" common in the aerospace industry to mathematically describe the task of certification.

An essential component in our exploration is the characterization of modeling error including errors in both physics models and probabilistic models. We pursue two mathematical formulations, Polynomial Chaos Expansions and Neural Networks, that permit to simultaneously investigate both errors in a consistent fashion. Our adopted formulations further tackle another challenge in product certification, namely the computational burden imposed by the necessity of high-fidelity simulations within a statistical approach.

This work builds upon a previously introduced simulation-based framework for prediction of design allowables of composite laminates, aiming to deepen our understanding of the impact of specimen size on the updating process within the framework. We focus on a hybrid Carbon-glass 4-ply laminate with 30mm wide unit cells that incorporate a staggered formation of carbon and glass tows across plies.

Our initial framework leverages randomized probability distributions for the constituent material properties, treating the fiber and resin components as random variables with 2 layers of uncertainty. This framework utilizes a numerical model to propagate the uncertainty of material properties to quantities of interest. Subsequently, test data is incorporated to update the material property distributions, refining our predictions of quantities of interest.

In this current investigation, we extend this framework by examining the size effect of specimens used in the data updating step. Employing an LS-DYNA RVE analysis, our numerical model represents the hybrid composite as an assembly of multiple "unit cells." Sub-models of varying widths are extracted from random locations within the larger model, simulating specimens of different sizes. Tension analysis is conducted to observe key QoIs, including the modulus of elasticity, peak stress, and strain at peak stress. The results reveal a compelling trend: as specimen size increases, the variance in observed properties decreases, and extreme values converge toward the means of the distributions. Integrating size effect information into the design allowables prediction process, particularly when utilizing the A-basis/B-basis allowables derived from the 1st/10th percentiles of the distributions, becomes imperative. By assimilating size effect information, this work contributes a critical building block towards a comprehensive analytical framework for certifying the reliability and safety of hybrid composite laminates in engineering applications.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEURAL NETWORK ENHANCED DIFFERENTIABLE MESHFREE METHOD FOR MODELING INELASTIC MATERIALS

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ABSTRACT

Modeling inelastic materials is crucial for advancing structural analysis, manufacturing, biomechanics, and diverse engineering challenges. Although data-driven machine learning approaches have been recently used for forward and backward problems, their accuracy and efficiency are limited in realistic engineering scenarios, particularly those involving nonlinear materials. In this presentation, we extend a recently proposed machine learning-enhanced meshfree approach, the neural-integrated meshfree (NIM) method, based on hybrid approximation, to simulate inelastic materials. NIM is a differentiable meshfree discretization solver enabling end-to-end gradient-based optimization and data-driven modeling. Our focus is on demonstrating improved modeling of inelastic materials by incorporating mathematical functions during neural network training within the NIM method. In addition, we explore various loss function formulations to encode plastic internal state variables and nonlinear material laws. To highlight the enhanced performances of the proposed method against existing approaches in the literature, several material models, including hyperelasticity and elastoplasticity, are considered in the study.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

XFEM-BASED MULTILEVEL SIMULATION STRATEGY ON HYSTERIC PERFORMANCE AND FRACTURE BEHAVIOR OF SEMI-RIGID PC CONNECTIONS

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ABSTRACT

Semi-rigid precast concrete (PC) connections exhibit a broad range of connection stiffness intervals due to their adjustable connection configurations. These connections often show complex and diverse time-varying hysteric performance and fracture behavior. Simulation methods based on a single dimension or scale encounter limitations related to crack closure interactions, numerical convergence, and computational power, making it challenging to simultaneously capture the hysteric performance and apparent fracture behavior under cyclic loading. Addressing these challenges, this study develops a multilevel simulation strategy that combines XFEM-layer with three-dimensional models. A three-dimensional model is employed to ensure the hysteric energy dissipation performance of components. XFEM-layer is utilized to capture their apparent fracture behavior, and motion coupling constraints on the central axial of the beam and column are employed to achieve time-varying synchronization of hysteric performance and fracture behavior. The simulation employs exponentially degrading cohesive elements to model the cast-in-situ-precast concrete adhesive interface, considering the bond-slip of steel-concrete and reinforcement-concrete during the fracture process using bidirectional nonlinear springs. To address the absence of a theoretical model accounting for surface effects in the cyclic stress-strain relationship from tensile to compressive states within the CDP model, this paper integrates the CDP model with the focal points model to establish a method for calculating the recovery path of compression stiffness. Results indicate that this simulation approach demonstrates acceptable accuracy in simulating the time-varying hysteric energy dissipation, stiffness degradation, and apparent fracture behavior of semi-rigid PC connections under cyclic loading. Moreover, this method is not limited to this component type, exhibiting higher-precision hysteric performance and fracture behavior simulation capabilities for cast-in-situ connections and equivalent cast-in-situ PC connections.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DURABILITY PERFORMANCE OF ENZYMATIC SELF-HEALING CONCRETE

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ABSTRACT

Ion permeability and resulting corrosion-induced degradation significantly hamper the sustainability of reinforced concrete structures. This study comprehensively evaluates the durability performance of a novel enzymatic self-healing concrete utilizing the ubiquitous enzyme Carbonic Anhydrase (CA). We propose a novel technique using a custom vacuum-assisted accelerated dye penetration test to assess the water/chloride ion permeability. The results demonstrate that CA-modified concrete exhibits substantially reduced dye adsorption, indicating superior water and chloride penetration resistance, with a remarkable 50% reduction compared to the control samples. Notably, the mechanical properties of the concrete were not compromised, emphasizing the promising potential of CA in extending the service life of concrete structures. Additionally, the simulation of diffusion provides insights into permeability coefficients and penetration depths in mortar and cement paste. Complementary analysis, including computed tomography (CT) scanning offers detailed insights into the mechanism of CA in enhancing concrete durability. This research underscores the significant role of CA in developing sustainable infrastructure, contributing to reduced CO2 emissions and cost savings over the life cycle of concrete structures.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIERARCHICAL ELASTOPLASTICITY OF CORTICAL BONE: OBSERVATIONS, MATHEMATICAL MODELING, VALIDATION

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ABSTRACT

While the mechanical failure of bone is classically associated with the formation of microcracks, with sizes ranging from 50 to 300 microns, a variety of experiments and computations, including solid-state nuclear magnetic resonance tests,

molecular dynamics simulations, and mechanical tests on cuboidally or cylindrically shaped micropillars of bone extracellular matrix, have evidenced that the nanoscale source for material degradation and bone strength appears to be of plastic and ductile nature, coming from mutual dissipative sliding of hydrated hydroxyapatite mineral crystals within the extracellular bone matrix.

We here quantify the macroscopic strength effects of this nanoscale source, through a six-step hierarchical elastoplastic micromechanics model:

A non-associated Mohr-Coulomb plasticity model is adopted for the description of plastic events arising right at the nanolevel of the hydrated mineral crystals found within the ultrastructure of bone. The latter is first integrated in a fashion inspired by the so-called return-mapping algorithm which was popularized in nonlinear Finite Element analysis, and then combined with a hierarchical concentration-influence tensor concept, yielding elasticity and strength values throughout the entire hierarchical organization of bone. Finally, the six-step homogenization scheme is carefully validated against a broad selection of biochemical and biomechanical experiments.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PAIRING UAV-COLLECTED IMAGERY DATA AND MACHINE LEARNING FOR CORROSION DETECTION IN BRIDGE INSPECTIONS IN AREAS WITH CHAOTIC DATA

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ABSTRACT

New technologies provide opportunities to perform structural health monitoring tasks with emerging data streams. One of these new data streams is from unmanned aerial vehicles (UAVs). Use of UAVs coupled with computer vision offers a unique opportunity to complement structural health monitoring and non-destructive evaluation (NDE) technologies during bridge inspections in particular. This work focuses on use of machine learning and UAV-collected imagery data for corrosion detection in bridges. UAVs are beneficial for their mobility and ease of data collection, but they do not provide subsurface data which is crucial for a complete understanding of the effects of corrosion on steel structures. This presentation discusses pairing UAVs and image-based corrosion assessment methodologies to act as a “first-pass” bridge inspection, which aims to determine whether a bridge needs further inspection.

Prior work has shown that corrosion segmentation algorithms are not simply transferable across datasets, especially for UAV-collected datasets that have significant background chaos. The work presented in this abstract is based on imagery data collected in the field, which has been collected in a chaotic environment with foliage, which resembles corrosion in texture and color. It is important to validate developed algorithms on data representative of bridge inspections and evaluate performance on physical structures before these new technologies are deployed. In this study, data is collected using UAVs at two locations in Georgia to create a dataset that represents local bridge inspection conditions.

The proposed methodology integrates deep learning methods (Fully Connected Network (FCN)), image processing techniques, and the K-means algorithm to create a method for use in bridge inspections. The FCN removes the background of the images to reduce the effect of foliage resembling corrosion. The image processing techniques quantify texture and reduce lighting effects and the K-means algorithm segments corrosion. Experimental results show that the K-means algorithm outperforms other segmentation methods, including image thresholding and deep learning, with a recall of 0.78 and mIoU of 0.72. Thus, the newly developed method can be a promising tool to improve the efficiency and safety of bridge inspections by reducing the need for full inspections on structurally sound bridges.

The principal contribution lies in the investigation of how UAVs and computer vision can best be deployed for bridge inspections, addressing challenges present in areas where the surroundings of the bridge present confusion for computer vision algorithms. This presentation discusses the optimal implementation of corrosion segmentation algorithms in the field.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING GRAPH BASED DEEP REINFORCEMENT LEARNING FOR INSPECTION AND MAINTENANCE OPTIMIZATION

Daniel Hettegger[1], Lisa Roßgoderer[1], Daniel Koutas[1], Alois C. Knoll[1] and Daniel Straub[1]*

[1]Technical University of Munich

ABSTRACT

Maintenance of deteriorating infrastructure imposes significant costs on owners and society. As a result, the development of efficient strategies for inspection and maintenance is crucial. Traditional approaches address these challenges using mainly fixed policies, heuristics, and human intuition. However, these approaches are often suboptimal and leave room for improvement. Thus, in recent works, deep reinforcement learning has been successfully applied to optimize maintenance actions in deteriorating systems [1].

In this work, we present a novel approach to optimize the inspection and maintenance task for deteriorating infrastructure systems based on graph convolutional reinforcement learning [2]. The proposed multi-agent architecture operates directly on the nodes of the graph, which potentially has several advantages to non-graph approaches by leveraging the structure of the problem to make decisions. This enables operation on a given problem even if there are underlying structural changes during deployment, such as new edges and nodes, and allows the trained policy to operate on graphs of varying size, where many other approaches would have to be retrained.

We evaluate our approach in an energy grid case study and compare it to relevant heuristic policies and deep reinforcement learning baselines.

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EFFECTS OF REACTIVE PERMEATING FLUID ON DEFORMATION OF ELASTIC SOLIDS IN COUPLED POROUS SYSTEMS

John Hickman[1], Ignasius Wijaya[1], Arif Masud[1] and Scott Roberts[2]*

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ABSTRACT

This talk presents a mixture model for chemo-mechanical response for a fluid-solid system influenced by heat transfer, large deformations, and chemical reactions. Due to the introduction of the reactive fluid, a moving front is generated that spurs material evolution of the porous solid. Governing equations in these systems, particularly the diffusion-reaction equation, can develop sharp boundary and/or internal layers indicated by specific material parameter relations (i.e., singularly perturbed case). In the singularly perturbed cases, spurious oscillations pollute the solution obtained with the Galerkin finite element method (FEM). To address this issue, we present a variationally derived, residual based VMS-Stabilized method that seeks to identify and suppress these erroneous numerical instabilities. In these same systems, which accommodate large deformations of chemically reacting fluids due to thermal oxidation, physical instabilities can arise that produce physically accurate fingering effects in the primary field solutions. Contrary to the “spurious oscillations” endemic of the singularly perturbed case, these effects are consistent with natural phenomena and experimental results. The main point of emphasis when implementing these VMS techniques then becomes identifying natural behavior, while successfully removing sources of numerical error that can propagate through the system, polluting the solution. Several benchmark test cases are presented and analyzed with special attention placed on preserving physically consistent results.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNIFIED ANALYSIS OF MESHFREE METHODS: COMPARISONS AND RESULTS

Michael Hillman[1], Joseph Magallanes[1] and Dominic Wilmes[1]*

[1]Karagozian and Case, Inc.

ABSTRACT

In this talk, I will give a general overview of meshfree techniques used to construct both the approximation to a field variable and the solution to a partial differential equation. I will focus on elastic behavior and the method of lines and omit inelasticity and space-time formulations.

For the approximation, two aspects are critical: accuracy (truncation error or completeness), and variational consistency for weak-form-based methods (passing the patch test). I will discuss how these represent the consistency of the mappings between nodal coefficients and stress points, and how this is common across all numerical methods indeed. Commonalities between methods will be discussed. I will present a unified formulation for encompassing all popular mesh-free approximations and methods (that I know of and can find), including, for instance, generalized finite differences (GFDs), SPH, moving-least squares, reproducing kernel, peridynamics, and diffuse, synchronized, and implicit gradients.

Several other key aspects of the methods are analyzed, such as convergence in smooth problems, dissipation and dispersion for homogenous elastic materials, proper representation of material softening, and tensile instability. Following [1-4] I will show that unless special care is taken, these properties are not guaranteed. Among the very few methods that have these essential properties, I discuss how the well-known reproducing kernel particle method with strain-smoothing satisfies all these aspects.

Next, several methods are evaluated in the simulation of challenging applications such as fragment-impact problems, in terms of the predictive power and also the selection of tuning of numerical parameters used to attain those (e.g. artificial viscosity in SPH).

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NUMERICAL AND EXPERIMENTAL ANALYSES OF A NEW TONOMETER BASED ON SOLITARY WAVES

Madison Hodgson[1], Ali Komaie[1], Piervincenzo Rizzo[1] and Samuel Dickerson[1]*

[1]University of Pittsburgh

ABSTRACT

A technique based on highly nonlinear solitary waves (HNSWs) has recently emerged to characterize engineering materials. It is based on the actuation and detection of solitary waves propagating along an array of spheres, the last of which is in dry point contact with the material to be evaluated. The method makes use of the so-called HNSW transducer, which consists of the array, an electromagnet, and a sensor. In the study presented in this paper, a portable, small wireless transducer was designed, assembled, and tested to test small or soft samples without any wired connection to electronic test equipment. The reliability of the new device was proven by completing a series of experiments in which a soft tissue simulating the cornea was subjected to varying internal pressures. The experiments successfully proved that the instrument can accurately operate without the support of electronic equipment and that some of the characteristics of the HNSWs can be related to the intraocular pressure.

Tropical cyclone induced winds, surge-wave, flooding and impacts on infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STORM SURGE VULNERABILITY OF IDEALIZED DELTAIC LANDSCAPES UNDER FUTURE SEA LEVEL RISE SCENARIOS

Sayed Omar Hofioni[1], Peter Bacopoulos[1], Celalettin Emre Ozdemir[1] and Matthew Hiatt[1]*

[1]Louisiana State University

ABSTRACT

Deltas have been immensely important landforms throughout the civilization and are currently home to millions of people as well as productive and diverse ecosystems. However, low-lying deltas are vulnerable to the adverse effects of the changing climate due mainly to sea level rise and more intense storm surges due to the tropical cyclones. Therefore, assessing the vulnerability of alluvial deltas to storm surges amid sea level rise is crucial. To this end, this study focuses on assessing the vulnerability of different delta morphologies under impacting factors such as rising sea levels, storm surges and river borne sediment composition and quantity —due to their impact on the elevation and the channelization of the delta morphology—. A conceptual analysis for the vulnerability of alluvial river deltas is carried out by using the delta morphologies obtained from the reduced-complexity DeltaRCM model considering different sea level rise scenarios and sediment composition. The topo bathymetric data of the delta morphologies obtained are used in the ADvanced CIRCulation (ADCIRC) model to assess the impact of the tropical cyclones on these idealized delta domains. The inundation of the deltaic landscape during tropical cyclones under increasing sea levels are investigated. Various modeling scenarios are considered to study the impact of the sea level rise, sediment composition, and tropical cyclone intensity on the vulnerability of river deltas in an idealized domain. Our preliminary results suggest that the deltas' vulnerability is primarily governed by its hydrologic connectivity and elevation, which depend on the sediment composition delivered by rivers.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHOTOGRAMMETRIC RECONSTRUCTIONS FOR BRIDGE INSPECTIONS: PERFORMANCE EVALUATION OF AUTOMATED DRONE ACQUISITION AND INSPECTION REPORT REPORT LOCALIZATION

Rodrigo Sarlo[1], Michael Sanchez[2], Emilie Hollingsworth[1] and Ishan Pradhan[1]*

[1]Virginia Tech
[2]Sanchez Engineering Services, LLC.

ABSTRACT

While there is a wide-spread precedent for the usage of data obtained during drone flights to create 3D models via photogrammetry, its application to the structural inspection process is fairly recent. As such, there is a lack of understanding of the trade offs between model quality and utility. In most field applications, it is impractical to create ultra-high-fidelity reconstructions, thus the efficiency of data capture and model creation will largely determine the success of this technology. This work evaluates model and software performance through key metrics describing the utility and efficacy of photogrammetric models created for the purpose of providing an organization framework for structural inspection reports. These metrics describe all phases of this multi-faceted approach, including drone acquisition and model creation, iterative model refinement, and localization of inspection report data via imbedded images. While individual photogrammetry pipelines and software packages are numerous and have been thoroughly evaluated in controlled conditions, this work focuses primarily on evaluating performance according to metrics that can be controlled for in the field. These metrics are used to adapt a drone's path planning in order to maximize the utility of a photogrammetric reconstruction, while avoiding unnecessary detail. This work focuses heavily on process feasibility in field conditions, where more refined processes, high fidelity modeling, and physically delicate tools may struggle to perform. In the spirit of actionable solutions, this work showcases the performance of our method through a field use case in collaboration with the Virginia Department of Transportation, where the base 3D reconstruction is used as a scaffold to localize images taken manually by inspectors.

Repair and assessment of deteriorating critical infrastructure
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CYCLIC ACTUATION BEHAVIOR OF IRON-BASED SHAPE MEMORY ALLOYS FOR USE IN SELF-CENTERING COLUMNS

Huanpeng Hong[1], Bora Gencturk[1] and M Saiid Saiidi[2]*

[1]University of Southern California
[2]University of Nevada, Reno

ABSTRACT

One potential application of iron-based shape memory alloys (FeSMA) is in post-tensioning concrete structures to provide recentering capability under strong seismic loads. Experimental studies have been performed on the use of FeSMA to strengthen or repair existing structural components such as steel or concrete beams. In addition to the application in structural rehabilitation under gravity loads, FeSMA also has potential for use in self-centering columns. However, the basic material properties, such as strength, ductility, recovery strain, actuation stress, low-cycle fatigue resistance, and temperature dependence, of FeSMA related to self-centering bridge applications have not been studied thus far. To fill this knowledge gap and determine the feasibility of using FeSMA in self-centering columns, this study performed a comprehensive material characterization of FeSMA. The behavior of FeSMA was investigated both before and after thermal stimulation also known as actuation. The strength, ductility, and recovery strain of FeSMA before actuation were tested under temperatures ranging from -40℃ to 50℃. The recovery stress, low-cycle fatigue resistance, and deformability of FeSMA after actuation were tested under a wide range of control variables including post-actuation temperatures ranging from -40℃ to 50℃, prestrain levels ranging from 4% to 30%, and low-cycle fatigue loading amplitudes ranging from 0.5% to 1%. The results from this study demonstrated that FeSMA exhibits excellent deformability, cyclic actuation stability, and low-cycle fatigue resistance under ambient temperatures from -40℃ to 50℃. Furthermore, it was found that increasing the prestrain level can effectively increase the post-actuation strain amplitude before the actuation stress is reduced to zero. A prestrain level of 15% to 20% is recommended for practical applications of FeSMA in self-centering columns. The research findings from this study demonstrated the feasibility of using FeSMA in self-centering columns subject to extreme loads.

ASSESSING THE TYPHOON HAZARD FOR THE SOUTHEAST COAST OF CHINA USING THE CHANGE-OF-MEASURE METHOD

Xu Hong[1] and Zhiqiang Wan[2]*

[1]Hefei University of Technology
[2]Northwestern Polytechnical University

ABSTRACT

Typhoons (also known as tropical cyclones) cause tremendous economic losses and human fatalities on the mid- and low-latitude coastal regions every year. For the purpose of mitigating typhoon hazards, it is desired to determine the probability distribution information of the annual extreme wind speed at the surface induced by typhoons. It typically involves analyzing the propagation of the randomness from the sources to the typhoon-induced surface wind by the Monte Carlo simulation. Generally, the typhoon-prone region includes many sites of interest and the probability distribution of the randomness differs from one site to another, therefore, if the traditional technique is utilized, analyses need to be conducted for every single site separately, inevitably resulting in great computational effort. A similar problem is also met in the field of imprecise probabilities, where the probability distribution of the random source could be uncertain. Recently, the change-of-measure method has been developed to circumvent this obstacle by carrying out the deterministic analysis only for the selected points associated with the reference probability distribution of a random source and by changing the assigned probability of the selected points for the other probability distributions. In this study, the change-of-measure method is applied to the issue of assessing the typhoon hazard for six cities on the southeast coast of China. The deterministic points are selected according to the probability distributions for the randomness at Xiamen and the assigned probabilities of the selected points for other sites are calculated. The typhoon-induced surface wind is simulated for each selected point with a parametric wind field model. The probability density evolution method is then utilized to analyze the probability distribution annual extreme of the typhoon-induced surface wind. The comparison between the results from this study and those by the Monte Carlo simulation validates the fidelity of the proposed method.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PARAMETRIC GRID CONVOLUTIONAL ENCODING FOR PHYSICS-INFORMED NEURAL NETWORKS

Mehdi Shishehbor[1], Shirin Hosseinmardi[1] and Ramin Bostanabad[1]*

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ABSTRACT

Solving Partial Differential Equations (PDEs) is crucial to modeling physical phenomena, yet their complexity poses significant challenges in certain applications. Recent advances have brought many flavors of Physics-Informed Neural Networks (PINNs) to this field as mesh-free alternatives to conventional solvers. However, PINNs fall short in approximating solutions for complex PDE systems, e.g., Navier-Stokes equations, especially in unsupervised settings where no labeled data is available in the domain. Moreover, they are known to suffer from spectral bias, i.e., they tend to learn lower-frequency components of the solution more efficiently than the higher-frequency components. In this presentation, we will introduce a novel encoder-decoder architecture designed to address these shortcomings. Our model maps the input space to a structured high-dimensional feature space via a parametric grid convolutional encoder and enhances the hidden states of the ensuing NN by subsequent connections from the corresponding features. Our model can handle irregular 3D domain geometries despite employing cartesian grids. It also benefits from a gradient-based technique to balance loss terms during training. By performing Power Spectral Density (PSD) analysis on the error profiles, we demonstrate that the given structure to the learning process effectively mitigates spectral bias. Additionally, we compare our model against benchmarks to showcase its superior solution accuracy across various PDE systems.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE ROLE OF NANO SILICA IN REGULATING THE HYDRATION OF ALUMINOSILICTE PHASES AND THE HINTS FOR EXPLORING LOW-CO2 CEMENT

Pengkun Hou[1] and Xin Cheng[1]*

[1]University of Jinan

ABSTRACT

Replacing cement clinker with supplymentary cementitious materials (SCMs, mainly composed of aluminosilicate phases) is one of the most promising technologies for reducing carbon dioxide emissions in the cement industry. However, the decrease in the quality of SCMs highlights the necessity of active excitation technology, and the use of nanomaterials, especially nano silica (NS), for the excitation of cement-based materials has received widespread attention in recent years. However, a series of research results have shown that NS exhibits opposite effects in regulating the hydration and hardening properties of aluminum and silicon phases. Therefore, it is crucial to correctly use nano control technology, especially in high alumina silicate systems. The report will first introduce the research results of NS on the hydration regulation of C3S/C3A system, reveal its mechanism of action, and then take supersulfate cement as an example to introduce the inspiration and thinking of relevant basic research on the performance stimulation of high content aluminosilicate low-carbon cementitious materials.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING ROBOT-SOIL INTERACTION POLICY OPTIMIZATION THROUGH HYBRID DIFFERENTIABLE SIMULATION AND GLOBAL SEARCH TECHNIQUES

Cheng-Hsi Hsiao[1] and Krishna Kumar[1]*

[1]University of Texas at Austin

ABSTRACT

This study explores using differentiable simulators for policy optimization in robot-soil interactions. Differentiable simulators offer a direct pathway to gradients within the loss landscape, resulting in more efficient Optimization of policy parameters than conventional model-free reinforcement learning methods. Despite these benefits, challenges arise in scenarios with complex contact dynamics and discontinuous functions, particularly for gradient-based Optimization. Discontinuities in the loss landscape can lead to issues like exploding or vanishing gradients, plateauing, and convergence to suboptimal local minima.

The research addresses these challenges through a specific case study that focuses on optimizing the initial angular velocity of a wheel with grousers rolling on granular material to reach a predefined target position. The granular physics and frictional contacts introduce discontinuities in the optimization loss landscape. We developed a differentiable material point method (MPM) using the Taichi programming language to model the robot-soil interactions. In differentiable simulations, computational tasks are decomposed into elementary operations, encapsulated within nodes of a directed acyclic graph (DAG). Inter-node connections, represented as directed edges, delineate the sequential data flow and dependencies among these atomic operations. The DAG representation of the simulator facilitates the systematic application of chain rule in automatic differentiation, enabling rigorous and efficient gradient propagation throughout the computational graph for optimization purposes. Taichi facilitates the tracking of gradients across variables, enabling effective gradient-based Optimization. The wheel is modeled as elastic material with high stiffness, while the granular material has a 45-degree friction angle.

The objective is to minimize the final distance between the wheel center and the target position by modifying the initial velocity. Using a pure Bayesian optimization with a Gaussian process, we reached the target distance of 0.4 m with a relative error of 2.5 % for a wheel with eight grousers rolling on sandy terrain. We adopt a two-step approach to mitigate issues like local optima and plateaus in computing gradients for discontinuous contact models. Bayesian Optimization is initially applied for a global search of the policy space, leveraging a surrogate model to quantify uncertainty and explore unknown regions efficiently. Subsequently, we employ gradient descent for local refinement.

We compare the performance of this hybrid differentiable simulation and global search approach against two model-free methods—Proximal Policy Optimization and pure Bayesian Optimization—and a baseline model of gradient descent with random restarts. The findings underscore the sample efficiency gains and advantages of incorporating gradient-based Optimization with global search for policy optimization.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SPACE-TIME MODULARIZED NEURAL NETWORK APPROACH FOR SHOCK WAVE MODELING

Tsung-Yeh Hsieh[1], Yang-Ming Tsai[1] and Tsung-Hui Huang[1]*

[1]National Tsing Hua University

ABSTRACT

In recent years, Physics-informed Neural Networks (PINNs) [1] has become a popular tool in the forward and inverse modeling of various partial differential equations (PDEs). The meshfree feature of PINNs and its universal approximation via neural networks enables a straightforward discretization and coding implementation on arbitrary geometry. However, it is still challenging for PINNs to solve certain types of problems, e.g. shock wave problems. The smooth neural network kernel selection often leads to either low convergence, unbalanced optimization, or over-diffusion in capturing the moving discontinuity in the space-time domain. To mitigate this issue, this study employs a specially designed neural network kernel and modularized neural network structure following the earlier work of Baek et al. [2], where here the spatial and temporal design of the modularized neural network is proposed for specializing in shock mechanics. Additionally, Total Variational Diminishing (TVD) penalization [3] is introduced to ensure thermodynamic consistency. The effeteness of the proposed method is benchmarked by solving various shock wave problems, including shock transportation, Burgers equation, and Euler’s equation.

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Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COUPLING BETWEEN SOIL MATRIC POTENTIAL AND OSMOTIC POTENTIAL

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[2]Colorado School of Mines

ABSTRACT

Soil matric potential and osmotic potential are widely accepted as two independent components of total soil water potential. However, laboratory observations repeatedly demonstrated that matric potential can vary with salt concentration, implying a potential coupling between matric potential and osmotic potential. To date, it remains elusive whether matric potential and osmotic potential are independent or not and why so, and a theoretical theory for quantifying the coupling between them is still missing. Herein, a theoretical model is developed to quantitatively explain this problem via a lens provided by a recent concept of soil sorptive potential. The proposed model substantiates that matric potential and osmotic potential are not independent. The increasing salt concentration can notably depress two variables underpinning soil sorptive potential, namely relative permittivity and electrical double layer thickness, leading to non-negligible decreasing (more negative) of matric potential in the high suction range, and increasing (less negative) of it in the low suction range. In turn, the soil-water interactions redistribute ions in soil water, raising osmotic potential, especially for clay with high cation exchange capacity. The proposed model shows excellent performance in capturing experimental data, validating its accuracy. A parametric study implies that the neglect of coupling effects can lead to a significant underestimation of soil hydraulic conductivity in the film flow regime.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NONLOCAL HYBRID ELASTO-PLASTIC MODEL BASED ON HOEK-BROWN CRITERIA WITH SEGMENTED FLOW RULE

Xiaokun Hu[1] and Haitao Yu[1]*

[1]Tongji University

ABSTRACT

In order to simultaneously describe the elasto-plastic and damage behaviors of rock under different confining pressure, a nonlocal hybrid elasto-plastic model based on Hoek-Brown criteria is proposed in this paper. The proposed model couples the non-ordinary state-based peridynamics (NOSBPD) method and the nonlocal differential operator method to eliminate the surface effect due to the incomplete integral region near the boundary, and to simplify the imposition of boundary conditions. A plastic constitutive model with the well-known Hoek-Brown criterion is integrated within this framework to accurately represent the nonlinear behavior of rock-like materials. The segmented flow rule is used as for different pressure conditions. A fracture criteriion based on the equivalent plastic strain capture the elasto-plastic fracture processes in rock-like materials. The dynamic relaxation method is combined with the return mapping method to address quasi-static nonlinear problems. The proposed model is verified by comparing its results with those from the Finite Element Method (FEM), as well as with experimental data from the literature. Numerical examples contain the conventional triaxial compression tests and compression tests of rock specimen with pre-existing flaws. Numerical examples demonstrate that the proposed model captures well the entire elasto-plastic fracture process for rock-like materials, including elasto-plastic deformations, crack propagation and progressive failure.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMIZATION OF AUTOMATED INSPECTION FOR INFRASTRUCTURE CONDITION ASSESSMENT BASED ON PHYSICS-BASED DIAGNOSTICS AND PROGNOSTICS

Zihan Wu[1]*, Zhen Hu**[2] *and Michael Todd*[1]

[1]*University of California, San Diego*
[2]*University of Michigan-Dearborn*

ABSTRACT

Automated inspection through the utilization of unmanned aerial or underwater vehicles has great potential to release humans from labor-intensive, boring, and dangerous inspection tasks for civil infrastructure condition assessment. While the current automated inspection methods, informed by the building information model, have shown promise in identifying defects automatically with the consideration of inspection time, the impacts of inspections on overall lifecycle cost management and physics-based analyses are largely overlooked. This research presents a novel framework for the optimization of automated inspections by enabling bidirectional information exchange between automated inspection and physics-based diagnostics and prognostics [1-2].

In particular, the inspection data is used to update the physics-based damage simulation model in the inspection-to-analysis direction. The updated physics-based simulation model then enables model-based failure prognostics, which can be used to guide the optimization of future inspection strategies and thus minimize the overall lifecycle cost in the analysis-to-inspection direction. Using the unmanned aerial vehicle (UAV) inspection of a miter gate as an example, we first build a connection between UAV inspection parameters (i.e., inspection distance, inspection interval, and maintenance threshold) and structural lifecycle cost. After that, we formulate an optimization model to optimize the inspection parameters by minimizing the cost per unit time (CPUT) based on physics-enabled pre-posterior analysis that integrates Bayesian model updating with failure prognostics and maintenance decision-making. Results of our miter gate application example show that the coupling between automated inspection optimization and physics-based diagnostics and prognostics can effectively determine the optimal inspection strategies that lead to minimized lifecycle costs. Even though the proposed framework is demonstrated using a UAV inspection example, it can be extended to other automated inspection methods as well.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A RECURSIVE LIKELIHOOD-FREE INFERENCE METHOD FOR MODEL-BASED DIAGNOSTICS AND PROGNOSTICS OF MITER GATES USING VIDEO MONITORING DATA

Jice Zeng[1], Michael Todd[2] and Zhen Hu[1]*

[1]University of Michigan-Dearborn
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ABSTRACT

Effective model updating under uncertainty method is indispensable for model-based structural health monitoring (SHM) of large civil infrastructures. Yet, the complexity of model updating could escalate significantly when computational models for SHM are connected in a multi-level manner. One example of such a model is the unobservable degradation model of miter gates. It is embedded in an observable structural analysis model and affects the structural response under dynamic water levels. The hierarchical model architecture and the presence of various uncertainty sources pose significant challenges to the derivation of a closed-form likelihood function, which is essential for Bayesian-based model updating methods. Moreover, recent advancements in sensing and image processing technologies allow for the collection of a substantial amount of video monitoring data through non-contact sensing techniques. The large volume of video monitoring data makes the derivation of the likelihood function even more difficult and adds an additional layer of complexity for model updating-based SHM.

This research introduces a novel recursive likelihood-free inference method to tackle the aforementioned challenges by using conditional invertible neural networks (cINN) [1]. A convolutional autoencoder is first employed to compress the high-dimensional video monitoring data into low-dimensional latent-space representation. A cINN model is then trained using synthetic data generated from a multi-level computational model, accounting for uncertainty sources in both damage states and simulation models. Subsequently, the resulting cINN is used in conjunction with the convolutional autoencoder to estimate the unobservable damage state using video monitoring data. To enable for continuous monitoring, we further integrate the cINN-based likelihood-free inference method with the particle filtering algorithm. The application of the proposed method to a degradation model of a miter gate demonstrates the efficacy of the method in updating the degradation model. The updated model can subsequently be used to predict the remaining useful life (RUL), providing valuable insights for model-based maintenance decision-making of miter gates.

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Computational geomechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATION OF EROSION AND FAILURE MECHANISMS IN SAND SLOPES UNDER SEEPAGE EFFECT

Zheng Hu[1]*

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ABSTRACT

The construction of infrastructure in coastal area has encountered numerous challenges related to slope stability, particularly due to the strong seepage induced by extreme rainfall events. Sand slopes are prone to particle loss and deterioration of mechanical properties under the influence of seepage, leading to slope instability and posing threats to urban development and human safety. Understanding the evolution of seepage-induced erosion and failure mechanisms in sand slopes is crucial for ensuring the stability of slopes and associated structures. In this study, a numerical simulation approach is employed to establish a model for the evolution of seepage-induced erosion in sand at the microscopic scale. The coupling of computational fluid dynamics and discrete element methods (CFD-DEM) is utilized to analyze the stress-strain behavior, skeleton structure, and pore evolution of sand samples. The comprehensive understanding of seepage erosion evolution, along with the macro and micro mechanisms, is investigated under different initial stress states and stress history conditions. Additionally, an improved method for calculating the critical hydraulic gradient of seepage erosion is proposed. Furthermore, a coupled finite element-discrete element method (FEM-DEM) considering fluid-solid coupling is employed to develop a rainfall infiltration analysis model for sand slopes. The model aims to study the progressive loss of soil particles and the overall slope instability under seepage conditions. By analyzing the evolution of the microstructure of typical regional sandy soil, the underlying microscopic mechanisms of slope instability induced by seepage erosion are revealed. This research provides new insights into the study of particle loss and failure of geotechnical engineering structures induced by seepage. It offers valuable guidance for analyzing the failure and catastrophic evolution processes of geotechnical engineering structures at macro and micro scales.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL GENERALIZABLE OPENING DETECTION MODEL FOR RAPID DISASTER RESPONSE

Hong-Bo Huang[1] and Rih-Teng Wu[1]*

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ABSTRACT

To quickly assess the safety of buildings and plan effective emergency response strategies, focuses often turn to the detection of openings, e.g., windows or doors. Particularly, compared to doors that are usually locked, windows may be a more viable option for rescuing team to enter the building and evacuate casualties during disaster events. Also, deformation in windows may indicate overall structural vulnerability and prompt warnings for severely damaged buildings. However, current state-of-the-art detection models often prioritize computational performance over generalization capabilities, leaving them incapable to handle complex and unforeseen environments, for instance, collapsed buildings. In this study, we develop a novel window detection model with high generalization capability, named Fopen-YOLO (i.e., Find opening-YOLO). The model is trained using non-disaster building images collected from Google Street View to evaluate its generalization ability in disaster scenarios. Compared to the baseline YOLOv5 model, Fopen-YOLO incorporates a Weighted Bidirectional Feature Pyramid Network for efficient multi-scale feature fusion, integrating low-level spatial information with high-level semantic information. Additionally, the proposed model contains an adaptive activation function, which uses learnable parameters to flexibly switch between linear and nonlinear activation. Furthermore, our model introduces the Coordinate Attention mechanism, efficiently combining spatial information with feature maps using channel attention decomposition. Finally, we utilize Ghost Convolution through cheap operations to reduce unnecessary feature map outputs, achieving model compression and efficient inferences. Results show that the proposed Fopen-YOLO outperforms baseline models on test datasets, with a 15.1% improvement in accuracy on Google Street View images, a 26.6% increase on images captured by unmanned aerial vehicles (UAVs), and a 21.2% boost for window detection in highly damaged buildings after earthquakes.

Keywords: Object detection, Deep learning, Generalization, Disaster responses, UAVs

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ANALYTICAL APPROACH OF DETERMINING LIFE-CYCLE COST OF DETERIORATING PIPELINES

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ABSTRACT

Life-cycle cost (LCC) analysis has been widely accepted in engineering for cost-effective decision making for structural integrity management including inspection and maintenance planning. The objective of this study is to develop an analytical approach to determine LCC for deteriorating pipelines considering failure probabilities, inspection scheduling, and repair criteria. Different from other civil infrastructure, LCC analysis in a pipeline system is more complicated due to two reasons: (1) pipeline's failure events occur at a local level, and the failure consequence can be costly, but it does not indicate the end of the service life of the whole system; (2) maintenance actions (e.g., inspection, repair) and failure events under service loading are highly correlated. Thus, the contribution of failure cost cannot be ignored or considered independently. To fully capture the correlation between the maintenance actions and failure events, there are two types of approaches to calculate LCC: simulation-based and analytical approaches. Analytical approach is attractive due to its ability to reduce computational cost and provides understanding of life-cycle performance of a system.

The proposed approach is developed based on a decision tree model by using analytical methods to evaluate events and considers the impact of the inspection schedules and possible repair actions on the probability distributions of failure times. Compared with the renew theory based analytical approaches, the proposed approach does not rely on the assumption that repair is a complete renew; thus, the proposed approach can incorporate various types of imperfect repairs and inspections in the life-cycle analysis. In addition, the proposed approach can explicitly examine the impact of the number of failure events on the LCC. The developed analytical approach is general and does not depend on any specific way to model the deterioration process, as long as the probability of failure can be computed.

To illustrate the proposed approach, a simple problem of a steel pipeline with a corrosion defect is used, where a stochastic model of corrosion growth is assumed and burst failure is considered as the pipeline failure mode. The case study indicates that finding an optimal inspection and maintenance planning is a compromise of the costs of inspection, repair, and failure. Also, the case study reveals that the inspection interval, repair threshold, the length of service life, and failure cost all have various influences on the expected LCC.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A CONSTITUTIVE NEURAL NETWORK ENHANCEMENT FOR MULTISCALE FRACTURE-TO-DAMAGE MODELLING

Tsung-Hui Huang[1], Yu-Chun Chou[1], Wen-Yi Hsieh[1], Yu-Zhen Li[1], Tsung-Yeh Hsieh[1] and Po-Yu Chen[1]*

[1]National Tsing Hua University

ABSTRACT

Multiscale fracture-to-damage modeling bridges micro-scale theoretical fracture mechanics with macro-scale phenomenological continuum damage models [1], presenting an effective approach for evaluating the failure of the material across different scales. However, its implementation often demands extensive microcracks problem-solving, leading to computationally intensive efforts constrained by specific microstructures. Recent offline-type homogenization approaches utilizing neural network training [2], is efficient, but may lack accuracy when extrapolating macro-scale online data from the offline training dataset. To address these limitations, this study introduces a constitutive neural network enhancement for multiscale fracture-to-damage modelling. This framework employs the constitutive artificial neural network (CANN) structure [3] to efficiently compute macro-scale damage evolution from micro-scale fracture or crack accumulation via a derived energy bridging equation, effectively avoiding extrapolation issues in online simulations. This methodology produces a homogenized surrogate model deployable in macroscopic scenarios with coarser mesh resolutions, significantly enhancing computational efficiency. Validation of this approach involves solving benchmark problems and comparing results with Direct Numerical Simulations (DNS), illustrating superior computational efficiency and efficacy.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STOCHASTIC RESPONSE ANALYSIS OF NONLINEAR STRUCTURAL SYSTEMS SUBJECT TO NON-WHITE AND NON-GAUSSIAN EXCITATIONS DESCRIBED BY PROBABILITY DENSITY FUNCTIONALS

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[3]Monash University
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[5]Tongji University

ABSTRACT

A technique is developed for determining the stochastic response of diverse nonlinear structural systems subject to non-white and non-Gaussian excitations described by probability density functionals (PDFLs). Specifically, the recent development of diverse sensor technologies, and the availability of massive amounts of measured data, facilitate a higher-order modeling and representation of stochastic processes, which was unfeasible a few years ago due to lack of sufficient data. In this regard, a mixed Gaussian PDFL is proposed herein due to its enhanced flexibility in modeling a wide range of stochastic excitation processes. Next, employing a change of variables treatment to the excitation PDFL, in conjunction with the governing stochastic differential equation, a closed form expression is derived for the system response joint transition probability density function (PDF). In fact, the response PDF is given as a functional integral over the space of all possible paths connecting the states of the response vector at the initial and considered multiple time instants. Notably, this functional integral, referred to as path integral in the literature, is rarely amenable to analytical evaluation [1]. Thus, an approximate calculation is pursued by considering the contribution only of the path with the maximum probability of occurrence [2]. This is known as the most probable path and corresponds to an extremum of the functional integrand. In this regard, the most probable path is determined by solving a functional minimization problem that takes the form of a deterministic boundary value problem (e.g., [3]). An indicative numerical example pertaining to a stochastically excited nonlinear oscillator is employed for demonstrating the reliability of the technique. Comparisons with relevant Monte Carlo simulation data are included as well.

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Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARATIVE STRUCTURAL ANALYSIS OF HISTORIC MIDWESTERN TIMBER BARN TYPOLOGIES UNDER WIND ACTIONS

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ABSTRACT

The aim of this work is to provide a comparative structural analysis of selected historic timber barn typologies under wind loads. Historic timber barns constitute a significant cultural heritage resource in the U.S. Midwest and are under threat from the compounding effects of aging, limited stewardship resources, and severe windstorms. This work lays the groundwork for population-level research by analyzing and comparing the behavior of different barn typologies and intra-typology variations under a variety of wind loading scenarios and load combinations. The results have implications for the efficiency and vulnerabilities of various forms, the modeling approach necessary to achieving the desired failure modes, and the categorization of typologies based on structural behavior. Together, these outcomes facilitate the creation of fragility functions via synthetic methods.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN OPTIMIZATION MODEL FOR WIND RETROFITS TO INFORM ALTERNATIVES FOR RESILIENT COMMUNITIES

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ABSTRACT

Wind-based hazards comprise some of the most devastating and costly natural disasters. Tornadoes, the deadliest disasters in the United States, can ravage communities, damaging buildings and critical infrastructure systems. To reduce the impacts of such disasters while constrained by budgetary and other restrictions, decision-makers must undertake the challenging task of evaluating which areas to prioritize with which retrofit actions. An integrated optimization model is developed, which can aid the decision process by informing improved allocation of retrofit spending under varying scenarios and constraints. The model incorporates the hazard impacts in terms of potential damages to various interdependent infrastructure systems and their resulting socioeconomic consequences and evaluates the effectiveness of alternative strategies for creating more resilient communities. For demonstration, a case study of the city of Joplin, Missouri, which is prone to tornadoes and was devastated by an EF-5 tornado in 2011, is presented. The damages to the residential buildings and critical infrastructure systems are first evaluated and validated with historical observations. Various objectives, including net economic losses, displaced populations, casualties, and recovery times, are constructed to incorporate the diverse priorities of community stakeholders. Then, based on different potential tornado intensity scenarios and probabilities, and under multiple budgetary constraints, optimal resilience enhancement strategies are determined, consisting of different combinations of structural retrofits of residential buildings, installation of tornado shelters, and power system improvements. The construction of the model allows for a flexible, interactive tool for community use, and the results enlighten different trade-offs in resilience planning, helping prioritize investments and compare potential alternatives.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NEW FRAMEWORK FOR MODEL UPDATING CONSIDERING INHERENT DISCREPANCY BETWEEN NUMERICAL MODELS AND REAL STRUCTURES

Chao-Sheng Hung[1] and Rih-Teng Wu[1]*

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ABSTRACT

This work aims to address the challenges in Finite Element Model (FEM) updating, proposing a novel hypothesis and methodology. Unlike existing studies that usually assume FEMs completely serve as a surrogate model for real structures, in this study we propose a framework that introduces a new hypothesis, which suggests that there may exist an inherent discrepancy between the FEM and real structures. This discrepancy, in other words, is the residual between the FEM simulation and measured structural responses. We formulate the residual as a function of structural parameters and propose to estimate the residual through data-driven-based approaches. To achieve model updating, we update the structural parameters by integrating measured accelerations, FEM-simulated accelerations, and the residual predicted by deep neural networks (DNN). Ideally, subtracting the summation of the FEM simulation and the residual from the measured acceleration should approach zero, allowing us to solve this problem with optimization algorithms. To validate our proposed approach, we implement a FEM based on the IASC-ASCE phase II benchmark dataset, and through this model, we simulated the measured response data that we required. In the first phase, we focus on updating one single structural parameter as a proof of concept. We train a Transformer-based DNN with simulated data to predict the residuals given various structural parameters. The model updating is then accomplished through Newton's root-finding method. Results show that a relative error less than 1% for the actual parameter to be updated is achieved, confirming the effectiveness of the proposed approach. In the second phase, we further address the updating of multiple parameters, demonstrating the potential in broader applications. Metaheuristic optimization algorithms, such as genetic algorithms and deep reinforcement learning are incorporated, with the ability to consider more uncertainties and make the updating process more adaptable to complex scenarios. Specifically, our implementation of the genetic algorithm approach achieves a relative error of 0.33% in estimating the reduction factor of column stiffness. The proposed framework could significantly impact structural health monitoring and maintenance management of infrastructures and even for applications in digital twins.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PUSHING THE LIMITS OF STRESS AND STRAIN MEASUREMENTS IN TRIAXIALLY-COMPRESSED SAND

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ABSTRACT

Triaxial compression tests have been used to study the bulk mechanical behavior of soils for decades. Only in the past two decades, however, have researchers begun to examine the structure and kinematics at play during these tests using in-situ x-ray tomography. Early studies using in-situ x-ray tomography could only examine structural changes on length scales larger than individual grains and thus only provided insight into the spatial distribution of dilation and compaction. More recently, micro-focus x-ray tomography and the development of robust 3D image analysis tools such as digital volume correlation (DVC) have provided access to the kinematics (displacements and rotations) of individual grains. The use of synchrotron beamlines and the rapidly advancing method of 3D x-ray diffraction has even more recently provided the ability to measure tensorial particle stresses, albeit in miniature samples and only for grains made of pure single crystals.

Here, we describe application of synchrotron x-ray tomography, 3D x-ray diffraction, and DVC to the examination of structure, grain kinematics, and grain stresses in triaxially-compressed sand. Although we have previously made these measurements in samples of 1,000 – 2,000 grains of single-crystal quartz, here we discuss two triaxial tests on 30,000 – 40,000 grains of either Ottawa sand or a synthetic sand of single-crystal quartz. These tests, performed at the PSICHE beamline at the SOLEIL synchrotron, allow us to study real materials and their true deformation mechanisms, without the finite-size effects present in prior experiments. We discuss data processing and experimental challenges as well as preliminary results describing the evolution of grain kinematics, fabric, strains, and stresses inside and outside of localization zones that develop during these tests. Connections are made to fundamental postulates of plasticity and localization theories.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCED DURABILITY OF CONCRETE WITH DURING- AND POST-CURE SHRINKING FIBERS

Mohammad Abdul Qader[1], Bismark Yeboah[1], Diarmuid Gregory[1], Mandar Dewoolkar[1] and Dryver Huston[1]*

[1]*University of Vermont*

ABSTRACT

This presentation describes the use of during- and post-cure active shrinking and matrix compressing fibers in concrete mixes to enhance durability. The underlying principle is that the shrinking fibers have two primary methods of property enhancement. The first effect is shrinking during cure and early age to control the microstructure and reduce the porosity, which enhances resistance to chloride penetration and water intrusion. The second effect is shrinking and compressing post-cure to induce a three-dimensional state of compression in the concrete to enhance strength, reduce cracking and extend post-cracking load carrying capacity. Two different approaches provide shrinking and compressive active fibers. One uses the pH sensitive polymer chitosan, which derives from the shells of crustaceans. High pH causes chitosan fibers to shrink. The high pH of ordinary Portland cement and many low-carbon footprint variants causes chitosan fibers embedded in a fresh mix to shrink during the cure cycle. The second approach is to mechanically prestress steel fibers by inserting water-soluble slugs into the circumference of cut rings. The presence of water in fresh concrete mixes initiates a slow dissolution of the polymer slug and releases the prestress in the ring onto the concrete matrix. Experimental results confirming the altered microstructure and enhanced durability of the chitosan shrinking fibers, along with enhanced post crack performance and altered acoustic emission signatures of the shrinking steel ring fibers will be presented. Proposed numerical simulations will also be discussed.

Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PREDICTING REAL-TIME DETERIORATION OF BRIDGES SUBJECT TO SPECTRUM-COMPATIBLE GROUND MOTIONS

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ABSTRACT

During the occurrence of earthquake events, bridges undergo seismic deterioration due to the dynamic forces at play. Recently proposed formulations based on Stochastic Differential Equations (SDEs) can capture the instantaneous effect of specific ground motion time-histories on the evolution of the system, by interpreting the corresponding deterioration as a rapidly evolving but still gradual process, rather than a discontinuous shock process. These formulations overcome the limitations of established practices that disregard the damage accumulation within the shocks and only look at the total effects of the ground motion.

While the recent literature has confirmed the hindcasting capabilities of such SDE models when calibrated based on the results of Finite Element Models (FEMs), the forecasting capabilities remain to be explored. In particular, it has been observed that calibrating the models based on the effects of a set of unrelated ground motions does not produce satisfactory results in terms of forecasting. As such, for this presentation we perform the calibration based on a set of spectrum-compatible ground motions, i.e. ground motions that share frequency characteristics. We investigate the degree of accuracy of the calibrated model compared with the results from the FEMs and compare it with similar results obtained by calibrating the models based on a set of unrelated ground motions. The deterioration models produced in this paper can be used for forecasting purposes at the location of interest, as future earthquake events are realistically going to share the spectrum characteristics with the ones used for calibration.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A UNIFIED CONSEQUENCE SCALE TO ACCOUNT FOR CUMULATED EFFECTS IN MULTI-HAZARD ANALYSIS

Leandro Iannacone[1], Kenneth Otárola[1], Roberto Gentile[1] and Carmine Galasso[1]*

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ABSTRACT

Multi-hazard analysis investigates the intricate dynamics among multiple hazard events and their resulting impacts. Interactions can be categorized broadly into two different types: Level I interactions manisfest through the hazard occurrences themselves (i.e., hazard events affecting the probability of occurrence of subsequent hazards, e.g., mainshocks influencing aftershock rates); Level II interactions manifest instead through the consequences of the hazards, leading to cumulated effects (e.g., the consequences of a flood may depend on the pre-hazard condition of the system, which a preceding hazard might have altered). Level I interactions inevitably lead to Level II interactions. However, Level II interactions can also originate from hazards that do not exhibit interactions at Level I (e.g., earthquake followed by flood).

Accurately quantifying Level II interactions is crucial to performing Life-Cycle Consequence Analysis of complex engineering systems, as these interactions directly affect the expected consequences (financial or societal) over the system's service life. However, challenges arise as consequences stemming from different hazards are often measured on distinct scales when examined independently. For instance, earthquake damage is commonly assessed based on the structural reliability of components, considering factors such as the presence of cracks, yielding, and observed local/global collapses. In contrast, flood damage is typically assessed based on the impairment of non-structural elements like appliances and furniture due to their contact with water.

Within the context of a multi-hazard analysis framework, there arises a necessity to harmonize these diverse scales to effectively capture Level II interactions across hazards. This presentation explores this issue by identifying the varied scales used to quantify damage from different hazards (such as earthquakes, floods, wind, and landslides) and highlighting their commonalities. Subsequently, a fault-tree analysis method is developed to translate consequences arising from different hazards into a unified and consistent scale. A case study is presented to illustrate the implementation of this unified scale within multi-hazard analysis frameworks for Life-Cycle Consequence Analysis.

VALUE OF STRUCTURAL HEALTH MONITORING BASED ON LINEAR BAYESIAN FILTER

Francesca Marsili[1], Leandro Iannacone[2] and Sylvia Keßler[1]*

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[2]University College London

ABSTRACT

Value of information (VoI) analysis can be used to assess the benefit of monitoring the health of infrastructure such as bridges and waterway locks. Such information supports decision-making processes, guiding operators towards the best actions for the infrastructure. In recent studies, VoI analysis is integrated with the modeling of the temporal evolution of structural conditions, so that the value of Structural Health Monitoring (VoSHM) can be assessed over the life cycle of the infrastructure. However, none of these studies considers the ability of the measurement system to detect small changes and its impact on the assessment of the VoI.

This contribution presents an approach to VoI assessment based on the concept of minimum change detectability and Bayesian linear filters. By exploiting a feature of the Kalman filter whereby posterior covariance is independent of observations, it is possible to predict the minimum shift in the mean value of a structural parameter for which its posterior density function would exceed a user-defined safety threshold. By constructing the decision tree and considering the cost of monitoring and maintenance, the value of detecting smaller changes can be estimated, which is the value of early change detection and performing preventive maintenance.

As a proof of concept, this approach is applied to evaluate the VoSHM provided by the monitoring of corrosion in reinforced concrete. The VoSHM is compared with the VoI associated with other nondestructive tests.

The contribution then discusses the implications of applying Bayesian linear filters in SHM for parameter change detection, the main one being the development of refined scales for structural condition assessment before any data from the changed state is available. Ultimately, the VoSHM is the benefit brought by adopting these refined scales in maintenance management.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RELIABILITY AND ULTIMATE FAILURE ANALYSIS OF SHIP HULLS UNDER CYCLIC BENDING LOADS

Mohammad Ibrahim[1], Aws Idris[1] and Mohamed Soliman[1]*

[1]Oklahoma State University

ABSTRACT

During normal operation, ship hulls are subjected to cyclic bending due to wave interaction. Accordingly, assessing the ultimate bending capacity is a crucial part of the collapse analysis of ship structures. Traditional approaches for quantifying hull reliability with respect to ultimate failure assume monotonically increasing bending moments while evaluating the flexural capacity of the hull [1]. However, recent research has shown that the hull resistance can drop significantly when the ship is subjected to high cyclic bending moments [2], introducing the cyclic ultimate strength concept for ship hulls [3]. Nevertheless, the effect of the drop in ultimate strength due to prior cyclic loading on the hull reliability presents a gap that needs to be addressed. Moreover, comprehensive investigations are still needed to evaluate the impact of the number of load cycles on ship hull integrity under cyclic loading. This is crucially needed to understand how the load cycles affect the hull integrity and the reliability of the ship structure.

This presentation discusses the results of a comprehensive study aiming to quantify ship hull reliability under cyclic loads. Finite element (FE) analysis of a ship hull section is used to quantify the hull capacity under various cyclic loading scenarios. The effect of initial geometric imperfections and residual stresses due to hull fabrication are considered in the FE simulations. Monte Carlo simulations are next utilized to evaluate the failure probability and hull reliability under different navigation scenarios. Artificial neural networks are utilized to surrogate the numerical analysis and accelerate the probabilistic simulations. The probabilistic simulations consider uncertainties in material properties, operational conditions, and environmental factors. The research outcomes are illustrated on a VLCC tanker operating in the North Atlantic Ocean. The presented research provides deeper insight into hull girder capacity, fostering safer, more durable, and more reliable marine structures.

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Uncertainty in geomechanical and geochemical processes: Their role on prediction of natural and engineered system behavior

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE VOID RATIO DISTRIBUTION IN RESPONSE TO JACKING INSTALLATION OF DISPLACEMENT PILES: FINDINGS FROM PHYSICAL MODELING

Amin Barari[12] and Lars Bo Ibsen[3]*

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[3]*Aalborg University*

ABSTRACT

A series of large-scale static compression tests were performed on tapered pile diameters 76 mm and 89 mm in dry and saturated soil conditions. Each test consists of multiple sub-tests with respect to determination of in-situ Baskarp Sand No.15 conditions and bearing capacities of the piles. The key findings discussed here are based on results from the pile installation by a jacking method, static load test (SLT) and the influence of penetration rate of tapered piles upon jacking in silica sand.

The Post-installation CPT probes suggested that the displacement pile jacking lead to a densification pattern all the way to the final installed depth in dry loose sand. By contract, with an increase of pile diameter from 76 mm to 89 mm, jacking results in dilation in the vicinity of displacement pile extended to a full depth with a narrow region above the ~1.8D_pile, where the soil was densified. The tendency to exhibit dilative behavior, fully turned into densification at a distance of 5.5D_(pile).

Pile jacking leads to densification in dense sand outside the pile, with the exception of dilative behavior when a pile in saturated sand is concerned, e.g., soil surrounding smaller pile exhibits dilation at depth 15D_pile near soil-pile interface. The tendency to demonstrate dilative behavior is even more pronounced as pile diameter increases (D_pile= P89), where it is tested in saturated soil.

Furthermore, it is interesting to investigate how much influence the penetration rate of the piles has on the measured bearing capacity. Doing so, the piles are jacked 90 mm in total after being fully installed, in which they are exposed to a three-step punch test repeatedly according to the following procedure.

20 mm with rate of 100 mm/min
5 mm with 1 mm/min
5 mm with 10 mm/min
10 mm with 100 mm/min
5 mm with 1 mm/min
5 mm with 10 mm/min
30 mm with 100 mm/min
5 mm with 1 mm/min
5 mm with 10 mm/min

Finally, the diagrams illustrating the difference between the static bearing capacity and the punch forces are presented.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SENSITIVITY ANALYSIS OF THE RELIABILITY OF CORRODED SHIP HULLS CONSIDERING INITIAL GEOMETRIC IMPERFECTIONS AND RESIDUAL STRESSES

Aws Idris[1] and Mohamed Soliman[1]*

[1]Oklahoma State University

ABSTRACT

The presence of initial geometric imperfections and residual stresses induced by welding is an inevitable consequence of ship fabrication and manufacturing processes. Past research revealed that incorporating these effects into the finite element (FE) models developed for the local components of ship hull girders (i.e., plates and stiffeners) has a considerable effect on structural performance. Consequently, this impact extends to influence the overall performance of the ship hull girder. Accordingly, investigating how these factors contribute to the variability in the structural capacity is essential for reliability assessment and for optimizing the design and developing reliability- or risk-based maintenance strategies. Recent research has shown that the uncertainty associated with the amplitudes of the initial geometric distortions may have a significant effect on the reliability of the local components of the ship under ultimate flexural loading conditions [1]. However, the quantification of how the randomness in these amplitudes affects the probability of hull failure under storm loading has not been conducted in literature. Moreover, the impact of these effects on the reliability of deteriorated hulls is also not well understood.

The work presented herein quantifies the effect of these imperfections and other input parameters on the reliability of ship hull girders utilizing Monte Carlo simulations. Additionally, it introduces a comprehensive variance-based sensitivity analysis approach, supported by artificial neural networks with a Bayesian regularization training algorithm, to identify the key input parameters influencing the reliability of deteriorating hulls under different operational conditions. The ultimate strength of the hull girder of an oil tanker is quantified using a high-fidelity nonlinear FE model that considers three types of initial geometric imperfections and residual stresses. The vertical bending moments experienced by the ship during its service life are also quantified. The results indicate that the amplitudes of initial geometric imperfections may not have a significant effect on the hull reliability; however, they are essential in obtaining the proper buckling shapes and stress distributions needed for design optimization.

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Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MICRO-MACRO HOPPER FLOW DESIGN FOR HANDLING GRANULAR BIOMASS MATERIALS

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ABSTRACT

The realization of the vast potential inherent in biomass-derived energy has encountered obstacles stemming from challenges in handling and feeding granular biomass feedstock. A prime example is observed in the widely employed hoppers, where issues manifest as arching, rate holes, and avalanche flow. These complications are attributed to gaps in understanding micro-scale material properties, macro-scale hopper design and flow performance. This study integrates physical experiments, validated numerical simulations, and data augmentation to formulate a machine learning-based design for hoppers handling granular biomass materials. The initial phase involves utilizing data from axial compression and shear tests to train a sequential deep-learning network. After validation, the network is applied to augment the laboratory-measured stress-strain behavior data for pine chips across varying moisture content and mean particle size. A meticulous calibration procedure refines a modified hypoplastic model capable of accurately representing the flow behavior of granular biomass materials. These calibrated models, combined with diverse initial packing and hopper operation conditions, are employed in hopper flow simulations through a validated Smoothed Particle Hydrodynamics code. Upon obtaining simulation results, a Principal Component Analysis (PCA) is conducted to discern key attributes of hypoplastic material parameters influencing hopper flow performance. Two feed-forward neural networks are subsequently trained and validated to establish connections between micro-scale particle attributes and critical hypoplastic parameters identified through PCA at the meso-scale, and the connections between critical material parameters, initial packing, hopper operation, and macro-scale flow performance matrix, respectively. In essence, these two neural networks collectively serve as a comprehensive design guideline for optimizing the flow of milled woody biomass materials within hoppers, catering to the needs of stakeholders in biorefineries and equipment manufacturing.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AERODYNAMICAL CLUSTER EFFECT OF ARRAYS OF INFINITE- AND FINITE-HEIGHT SQUARE CYLINDERS IN TURBULENT FLOW

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ABSTRACT

This paper studies the aerodynamical cluster effect of arrays of infinite- and finite-height 2x2, 3x3 and 4x4 square cylinders in various spacings. The array of infinite height square cylinders can be considered as a supertall buildings cluster, while the array of finite height square cylinders with a height-width ratio of 4 can be considered as a skyscraper building cluster. High-fidelity large-eddy simulations (LES) were carried out on a high performance computing system, considering the sensitivities due to different wind directions, wind speed profiles, turbulence intensity levels and integral length scales. Several wind tunnel experiments were also carried out for comparison. Wavelet analysis was performed to estimate the dominant vortex shedding frequency for different spacings, i.e., S= 0.5b, b, 1.5b, 2b, where b is the cylinder width. The analysis collectively suggested, for both smooth and turbulent incoming flows, the primary shedding frequency from the 2x2, 3x3 and 4x4 cylinder clusters can be scaled by the effective cluster size $We=(nb(1+ \varepsilon m/(n + m))$, where n and m are respectively the number of frontal column cylinders and the number of spacings across the frontal column of cylinders, $\varepsilon=S/b-1$ is the small difference between the spacing to building width ratio and unity. In other words, the primary shedding frequency of an array of infinite- and finite-height cylinders normalized by the effective cluster size We and the freestream velocity Ui, i.e. the Strouhal number $St = f*We/Ui$, is very close to that of an isolated single cylinder. It is to be noted that the value of the Strouhal number St is mostly dependant on the solid part of the cluster, with a small correction required for various spacings.

The consistent data suggest an evident aerodynamical cluster effect, which may help to quantify the vortex shedding frequency and the resulting wake flow behind an array of tall buildings. In addition, the data suggest that the turbulent incoming flow with a large integral length scale, e.g. greater than the cluster size, the dimensionless dominant shedding frequency St is reduced evidently compared to the smooth inflow. Furthermore, it is of great interest to assess the merging of the wakes from individual cylinders of an array. The location of the final stage of the merging in the far wake with various spacings was estimated. A scaling law for the merging distance to the cylinder array was explored, and will be reported in the symposium.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GLOBAL-LOCAL 3D DIGITAL IMAGE CORRELATION FOR FULL-FIELD STRAIN MAPPING ON CONCRETE STRUCTURES

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ABSTRACT

3D Digital Image Correlation (3D-DIC) is an optical technique to measure full-field strain measurement of structural deformations using changes in images from two cameras. The current application of the 3D-DIC in full-field measurements (e.g., displacement, strain) adopts one of two different DIC algorithms: subset-based algorithm and node-based algorithm. The subset-based (local) algorithm computes displacement by comparing the pixel intensity patterns within square pixel subsets from deformed and undeformed images with each subset's displacement computed individually neglecting the displacement continuities across the global field. While the node-based (global) algorithm discretizes the Region of Interest (ROI) into node-connected sections using target images to track all nodal displacements concurrently and adopts finite element (FE) analysis components to generate image meshes and optimize the displacement field. The majority of current commercial DIC systems use the subset-based algorithm because of its straightforward principles and efficiency. Nevertheless, the node-based algorithm may provide more accurate displacement outcomes as the consequence of the restriction resulting from the displacement continuity between neighboring components. A 3D-DIC method is needed to provide the comprehensive full-field strain measurement of structural deformation considering the challenging situations when there are cracks in development. The local algorithm is known for its precision as a localized measurement and the global-based algorithm is recognized for its comprehensive field coverage. The study will evaluate the effectiveness of both the local and global DIC algorithms and fuse them into a global-local DIC method to provide advantages of both high precision and wide-filed coverage in a practical strain mapping. A case study of ultra-high-performance concrete (UHPC) girders that are subjected to controlled loading conditions is monitored using multiple cameras and the developed 3D-DIC algorithm. Preliminary results demonstrate that the local-global DIC algorithm offers both higher accuracy in localized areas and a better understanding of the wide-field behavior of structural components under loading.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in bridge health monitoring: Data-driven and machine learning methods, indirect monitoring, crowdsourced mobile sensing
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SENSING BASED SIMULATION OF FORCE AND DISPLACEMENT IN REINFORCED CONCRETE BRIDGE COLUMNS SUBJECTED TO SEISMIC EVENTS BY USING PLASTICITY AND BAR-SLIP MODELS

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ABSTRACT

Accurate prognosis of bridge structures depends on continuous collection of structural data and proper translation of those data to meaningful structural quantities reflecting the history of structural loadings and responses. Reinforced concrete bridge columns subjected to seismic events undergo several discernible stages of damage before full collapse. This study aims to combine plasticity models and continuous sensing to explore how accurately the strain data gathered from a limited number of fiber optic sensors installed inside and outside of reinforced concrete bridge columns, could be used to continuously compute the forces and displacements experienced by the columns subjected to the seismic events.

In the present study, to calculate the bending moments and the corresponding shear forces in reinforced concrete columns, compressive stress distributions within the core and cover concrete were computed through the plasticity models of confined and unconfined concrete including stress-strain relations for loading, unloading and reloading scenarios identified by seismic signals of concrete strains. Similarly, the tensile and compressive stresses in steel reinforcing bars were computed by using kinematic hardening plasticity model for hysteretic stress-strain for loading, unloading and reloading cases detected by seismic signals of steel strains. Upon the calculation of stresses throughout the cross section, the resultant bending moment and corresponding shear force in the cross section were computed. To calculate the displacements, the distribution of strain signals across the concrete column cross section were used to compute the flexure and bar-slip components of the column displacement separately.

The proposed methods for computation of force and displacement were evaluated and validated through a hybrid simulation-based experimental program. Physical parts of the hybrid simulations include scaled models of reinforced concrete columns that were tested to failure under five consecutive seismic events with progressively increasing amplitudes. The columns were instrumented with six fiber optic sensors at the location of formation of plastic hinge. The six sensors included a pair of Arch sensors on the concrete surface, a pair of strain sensors on two of the reinforcing bars and a pair of deformation sensors embedded inside the concrete core. The study concludes that embedded and continuous sensing along with proper plasticity models are essential for accurate simulation of forces and displacements of a column subjected to seismic events.

MECHANICAL CHARACTERIZATION OF NANO-MODIFIED 3D-PRINTABLE ULTRA HIGH-PERFORMANCE CONCRETE: A NOVEL APPROACH

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ABSTRACT

As concrete 3d-printing becomes more adopted, the need for accurate modelling and experimental validation grows. Current strategies involve the construction and testing of full-scale printed elements for structural design, and material characterization using traditional cast concrete testing techniques such as uniaxial compression and split-tensile tests. This work addresses the gap between techniques by proposing a novel method to characterize mechanical properties of printable ultra high-performance concrete (UHPC) and ultra high-performance fiber-reinforced concrete (UHPFRC) which accounts for the unique geometric features of layered printed samples overlooked by cut or cored specimen. A 3d-printable UHPC mix is developed for this study using nano-modification to achieve the desired fresh state properties, which are validated with the manual flow table test prior to printing. Samples are printed using a 3-axis gantry system and piston extruder. Uniaxial compression, split tensile, and notched three-point bending tests are performed to printed UHPC and UHPFRC samples along their longitudinal, transverse, and normal directions. To allow representation of geometric features along the layers and boundaries of the printed samples while maintaining smooth, parallel surfaces for load application, a highly flowable variation of the UHPC mix is developed and used as capping material. Compressive strength, tensile strength, and fracture energy of the printed samples are obtained and compared to cast specimen from the same batch. Image analysis and 3d scanning are used for measuring pre and post capping, and failure modes are reported for each sample after testing. Results provide valuable insight into the effects of surface and inter-layer geometric features of 3d-printed concrete for mechanical characterization and calibration of computational models, while requiring significantly less material than full-scale structural tests.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADAPTIVE COVARIANCE TAPERING FOR LARGE SPATIAL DATASETS: APPLICATIONS TO STORM SURGE ESTIMATION

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ABSTRACT

Surrogate models have emerged as attractive data-driven, predictive models for storm surge estimation. They are calibrated based on an existing database of synthetic storm numerical simulations, and can provide fast-to-compute approximations of the expected storm surge. For typical applications these predictions refer to large number (up to hundreds of thousands) of spatial locations. Geospatial interpolation has been extensively used in this context, for either (a) database imputation, addressing missing data for nearshore nodes that have remained dry in some simulations, or (b) for the metamodel development itself, to infuse spatial correlation information in the prediction/calibration process. This work formally examines Gaussian Process (GP) techniques for supporting this interpolation. To accommodate the high-dimensional aspects of the problem, which entail the inversion of very large covariance matrices, adaptive covariance tapering is utilized. The tapers are adaptively chosen so that: (i) a target degree of sparsity is achieved for the spatial covariance matrix (simplifying inversion); while (ii) enforcing that each node has a sufficient number of neighbors with non-zero correlation (supporting a well-posed problem formulation). A novel strategy, relying on representative points, is developed for the selection of the covariance tapers under the aforementioned two objectives. The selection of these representative points is iteratively performed, using the discrepancy for objective (ii) to guide the decisions for new representative points. The proposed techniques are demonstrated utilizing the Army Corps of Engineers North Atlantic Comprehensive Coastal Study database. Results are shown for implementations using both selective save-points as well as the original numerical grid. This accommodates the examination of the computational efficiency and predictive accuracy of the proposed developments across datasets with different number of spatial locations.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING ASSISTED DESIGN OF ARCHITECTED MATERIALS FOR ENHANCED ENERGY ABSORPTION AND FAILURE STRENGTH

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ABSTRACT

Architected materials have received significant attention in the aerospace, automobile and medical industry due to their unique properties that make them ideal for various applications. These materials are characterized by their exceptional strength-to-weight ratio, thermal stability, and low density. The hexagonal arrangement of the atoms in a honeycomb lattice provides a unique combination of strength and flexibility, making these materials ideal for applications that require high performance and low weight, such as aircraft and spacecraft components, thermal protection systems, energy storage systems etc. Many modern structural applications require structures to absorb energy while maintaining the minimum amount of material added to the structure. To this end, conventional approaches to designing periodic microstructural geometry are probably saturated. Consequently, machine learning and artificial intelligence advances in this field are well suited to enhance the mechanical properties of artificially engineered lattice structures.

This study presents machine-learning models to predict the honeycomb lattice structure's failure band position and stress-strain behaviour under different loading conditions. The Sobol sampling technique is adopted to obtain the input parameters as random combinations of cell regularity (0, 0.3, 0.5, 0.7, 1), relative density (in the range of 3% to 9%), and elastoplastic material property (in the field of ± 20%). Simultaneously, we also proposed a sequential strengthening mechanism for identified failure bands in lattice structures for regular hexagonal lattices and a reinforcement strengthening mechanism for irregular geometries. This results in an increase of up to 30% in the energy absorption and ultimate stress for regular honeycomb lattices.

USING EXISTING OPERATIONAL CCTV-DERIVED VIDEO FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

The objective of this study is to investigate the potential for using already-installed operational CCTV cameras for the Structural Health Monitoring (SHM) of bridges. Computer vision is now commonly used for SHM applications, and has many advantage over the more traditional sensor deployment approach. Currently though, computer-vision-based SHM requires the deployment of dedicated cameras. This adds cost, complexity and makes it impossible to retrospectively analyse unscheduled events, for example an unforcasted extreme weather event for which computer-vision cameras could not be deployed in time. Video cameras are, however, already installed on many large structures in the form of operational CCTV. These cameras are mostly limited to security and traffic management applications, but there would be many advantages if they were also able to provide the video required for SHM. There are many technical reasons however why the video they produce might not be appropriate, hence the need for this research. To validate the feasibility of using CCTV cameras for SHM, this study will compare the results obtained from traditional sensor deployment methods to those obtained from CCTV-based computer vision. This study was conducted on the
iconic Clifton Suspension Bridge (CSB) in Bristol (UK).

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LLM-BASED STRUCTURE DRAWING GENERATION FROM NATURAL LANGUAGE DESCRIPTION USING RETRIEVAL-AUGMENTED GENERATION TECHNIQUE

Xin Zhang[1], Lissette Iturburu[1], Manuel Salmeron[1], Nicolas Villamizar[1], Xiaoyu Liu[1], Shirley Dyke[1] and Julio Ramirez[1]*

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ABSTRACT

In civil engineering, structure drawings are essential for designing and planning buildings and infrastructure. These detailed drawings encompass architectural layouts, structural elements, reinforcement details, as well as electrical and plumbing schematics. Key components include title blocks, plans, elevations, sections, and detailed views, with standardized symbols, scales, and line types for clarity. These drawings serve as crucial communication tools between architects, engineers, and builders, act as legal documentation, and provide a reference for future maintenance. They ensure that structures are safe, functional, and meet design specifications. As techniques have advanced, software such as AutoCAD, Revit, and SketchUp have become increasingly popular for enhancing the efficiency of producing structure drawings. The adoption of these software in design and construction has broadly enhanced efficiency and precision. Despite the advancements in software, transforming a natural language description into a structure drawing remains a laborious task for structural engineers, due to several factors. Firstly, creating structure drawings demands extensive professional knowledge, such as understanding specific standards and specifications. For instance, identifying a standard steel beam like "W1100*499" requires consulting standards or codes, a process that is time intensive. Secondly, the variability in descriptions from individuals with differing levels of expertise leads to inconsistencies. An inexperienced individual might refer to a rebar as "0.5 inch in diameter," whereas an expert might call it a "No.4 rebar," causing confusion in interpretation. Thirdly, the determination of geometric parameters and relationships in a drawing is often not straightforward from the description, necessitating additional calculations by engineers. Moreover, the manual process of drafting structure drawings is inherently time-consuming. To address these challenges, we introduce a novel AI-based method employing a large language model. This method is capable of comprehending varied natural language descriptions, processing these to extract necessary information, and generating code to produce the desired structure drawing in AutoCAD. It incorporates a retrieval-augmented generation technique, using externally sourced facts to enhance the accuracy and reliability of the language models. Our proposed approach enables the efficient and direct conversion of a structure drawing's natural language description into an AutoCAD drawing, significantly reducing the workload associated with manual drawing production.

Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEEP REINFORCEMENT LEARNING BASED HETEROGENEOUS SENSOR PLACEMENT UNDER NON-STATIONARY INPUT

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ABSTRACT

Monitoring infrastructures requires sensor networks that often consist of heterogeneous sensors. The design of such networks includes selection of the types of sensors and locations of instrumentation within the system. The combinatorial nature of sensor placement makes the optimization computationally costly in larger system with more candidate locations. In addition, the sensor measurements are associated with sensor noise, uncertainties in the model parameters, and the input excitation. These uncertainties make deterministic optimization methods intractable. In this work, a deep reinforcement learning-based method is proposed for the case of heterogeneous sensor placement that accounts for the uncertainties in the model parameter and the input excitation. The uncertainties in the model parameters are accounted for by assigning a priori probability distributions. To model the input excitation, the non-stationary nature of the ground motion excitations is considered. A Kanai-Tajimi model with an envelope function is used to generate the sample inputs. An information-theoretic objective function is used that quantifies the information gained about the model parameters in each measurement channel. A deep reinforcement learning algorithm is used to train an agent to maximize the expected gain from placing sensors in candidate locations in the system up to a budget constraint. The proposed framework is applied to examples of shear building models, and the results are compared to those of a population-based optimization method. Finally, transfer learning is used to improve the curse of dimensionality in larger systems, utilizing the agent trained on a small system as a pretraining for a larger system. Experiments on transfer learning are also presented for variations in system parameters and site-specific Kanai-Tajimi model parameters to illustrate the reusability of the outputs.

Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TRANSFORMING COMPLEX MODELS INTO ACTION: BRIDGING THE GAP BETWEEN ACADEMIA AND INDUSTRY WITH AI-POWERED PREDICTIONS IN ADVANCED MANUFACTURING

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ABSTRACT

Digital twin technology sits at the nexus of computer science, applied mathematics, and engineering, presenting transformative potential for advanced manufacturing. The application of digital twin concepts in manufacturing can yield cost reductions and increased profits. Despite substantial efforts by academics to construct high-fidelity simulation models mirroring real-world systems, the translation of these complex models into practical industry use cases remains a formidable challenge. This challenge often stems from the need for additional experimentation, or the steep learning curve associated with emerging technologies. To that end, we propose a collaborative mechanism for academics and industry stakeholders. Our proposal introduces an artificial intelligence (AI) agent designed to navigate this challenge by leveraging prior knowledge to predict material properties with limited experiments. The essence of our concept lies in the continuous learning capacity of the AI agent, refining its predictions as engineers accumulate more data. To illustrate this concept, we showcass how the AI agent can predict thermal conductivity based on limited tensile tests for additive manufacturing. This demonstration not only aims to underscore the potential of AI agents in streamlining experimental efforts but also seeks to foster robust partnerships between academia and industry. By doing so, we endeavor to highlight the practical applications of AI in facilitating the adoption of digital twin technology.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A THERMO-HYDRO-MECHANICAL FORMULATION FOR MODELLING FAULT SLIP OVER THE SEISMIC CYCLE

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ABSTRACT

Understanding the transition from fault aseismic to seismic slip is critical to limit the risk of fluid-induced seismicity and insure the safe utilization of the subsurface. During the evolution from aseismic to seismic rupture, shear deformation localizes into a thin and confined principal slipping zone within the fault gouge. The evolution and distribution of fluid pressure and temperature within the fault gouge material are key factors for the onset and nature (seismic or aseismic) of fault slip. Laboratory and field observations indicate that transient localization of fluid pressure and temperature often go hand in hand with strain localization during seismic rupture: as slip occurs on a fault plane, temperature increases due to dissipated energy, leading to a competition between thermal pressurization and dilatant strengthening. An accurate description of this thermo-hydro-mechanical multiphysics coupling controlling slip mechanisms is therefore essential to characterize the stability of fault slip.

In this contribution, we present a novel physics-based friction law adopting a thermo-hydro-mechanical coupling scheme together with a rate-dependent plasticity formulation. In particular, we considered the effects of energy dissipation as a driving mechanism for unstable slip and of dilatant strengthening as a stabilizing mechanism. We studied the multiple steady-states of the system and their respective stability by means of a numerical continuation technique. We also described the dynamic evolution of deformation, fluid pressure and temperature fields resulting in stick-slip sequences by considering an associated transient problem.

The model considered in this study is capable of reproducing a variety of fault slipping styles, including stick-slip sequences, continuous creep, and periodic slow slip events. In particular, we will present the impacts of dilatancy, fluid diffusivity, and thermal pressurization on the stress drop magnitudes and the duration of seismic rupture. The results presented here provide insights into the stability criterion for aseismic slip and the dynamic evolution of slip instability as a function of the physical (thermal and hydraulic) properties of the fault material and the boundary conditions (tectonic stresses and off-fault fluid pressure and temperature conditions). We discuss the implications of these results for characterizing the transition from stable aseismic slip to unstable seismic slip in the context of natural and induced seismicity.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

APPLICATION OF AUTONOMOUS SYSTEMS FOR NONCONTACT AGGREGATE STOCKPILES VOLUME MEASUREMENT

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ABSTRACT

Monitoring a stockpile’s volume is essential for managing storage, sales, and organization of material inventory. Various technologies, such as Total Stations (TST), Light Detection and ranging (LiDAR), and Global Positioning Systems (GPS), commonly used to obtain stockpile volumes; however, stakeholders, such as state Departments of Transportation, seek to find a faster, safer way to obtain an object’s volume with minimal workforce training. Unmanned Aircraft Systems (UASs) can potentially obtain measurements of stockpiles, but surprisingly not implemented. UASs may be used to obtain an object’s area, location, size, and volume; however, the effect of flight parameters such as Ground Sampling Distance (GSD) on measurement accuracy has not yet been investigated. We conducted a series of tests to establish if a stockpile volume can be determined using UAS and Pix4D software. The Pix4D output was verified with MATLAB in terms of camera calibration, GSD values, and stockpile volume. We completed several flights to measure the volume of irregular shapes, such as stockpiles, and regular shapes, such as steel boxes. The steel box and stockpile volumes were measured using Pix4D for all flights. The results indicated that the software could measure a regular object's volume with an approximate 5% error under different flight conditions. The volume of several stockpiles was measured and compared under different flight conditions. The results indicated that using a UAS and PiX4D resulted in reliable evaluations with differences of less than 8% . LiDAR was used to calculate the volume of two stockpiles, and the results were compared with PiX4D. The output revealed that the average volume difference between LiDAR and the UAS was less than 5% using conventional image stitching software; however, the procedure requires tremendous time and effort to identify the objects of interest. To reduce the processing time and labor associated with the measurement, a deep learning point cloud classification model is developed. Using total of 30 flights from stockpiles were used for training (5-million-point clouds of seven stockpiles). The model achieved an accuracy of 92% in correctly identifying points that belong to the stockpiles. The proposed model showed consistent results with PiX4D (5.5% average difference). The results indicate that users can automatically calculate object volume while significantly reducing the processing time and labor without negatively affecting the measurements using autonomous systems.

Keywords: Stockpiles, Volume measurement, UAS, Visual Imagery, 3D Model, Artificial intelligence, PiX4D.

OPTIMAL RETROFITTING POLICY FOR EARTHQUAKE-INDUCED LANDSLIDE HAZARD ON TRANSPORTATION NETWORKS USING GRAPH NEURAL NETWORKS

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ABSTRACT

Landslides pose a significant danger to transportation networks, as highlighted by the recent incident on Highway 1 in California [1]. The vulnerability of hilly terrains to landslides is intensified by triggering events, with earthquakes playing a prominent role as catalysts. A comprehensive response to the landslide risk is crucial, especially in regions marked by substantial income disparities, necessitating a holistic assessment. This study is driven by the need to cultivate a subtle comprehension of the repercussions of landslides, extending beyond immediate disruptions and emphasizing the interconnected nature of transportation networks.

The primary objective of this research is to develop optimal retrofitting policies that enhance the resilience of transportation systems while considering the differentiated impact on various income groups. To achieve these objectives, a novel Siamese Graph Convolutional Neural Network (GCN) [2] is developed. This innovative neural network architecture serves to approximate the increase in total system travel time for disrupted networks, offering a nuanced understanding of the impact of landslides on travel time. The Siamese GCN is trained to effectively capture the dynamic nature of disrupted networks, providing valuable insights into the magnitude of travel time increases associated with various landslide scenarios.

The optimization of retrofitting strategies is facilitated by genetic algorithms that consider the interconnected nature of transportation networks and aim to maximize the overall network efficiency and minimize disparities in welfare loss. The integration of genetic algorithms ensures that the retrofitting strategies are not only effective but also adaptable to diverse scenarios and dynamic conditions.

The application of this research extends to hillside areas prone to earthquake-induced landslides. By providing a comprehensive tool for enhancing transportation network resilience, the study contributes to the broader goal of creating more inclusive and resilient cities. The adaptability and versatility of the proposed framework make it a valuable asset for addressing various natural hazards, refining retrofitting strategies, and fostering the development of transportation networks resilient to dynamic environmental conditions.

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Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LOCAL SHEAR RATE OF POROUS MEDIA

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[1]Virginia Tech

ABSTRACT

This paper introduces the contact shearing rate soil particles undergo during triaxial compression. Geomaterials tested in a triaxial setup are often sheared using a constant strain rate determined based on the consolidation characteristics of the material being tested. In certain applications, such as rate-dependent plasticity, soil strength and deformation characteristics will be function of the loading rate. In other words, the rate of particles movement during deviatoric loading will dictate the strength/deformation of the soil. We utilized numerical simulations based on the discrete element method (DEM) to study the contact shearing rate between soil particles. We developed and exploited DEM flexible boundaries to replicate what physical soil specimen experience in triaxial tests. It is shown that the rate soil particles move during deviatoric loading is much lower than that applied globally during the test. Moreover, soil particles in a specimen consolidated at lower effective stress are shown to develop larger contact shearing rates when compared to specimens consolidated at larger effective stress. Furthermore, larger magnitudes of contact shearing rates develop for loose specimens, although the relative density impact on the contact shear rate vanishes at the critical state. Such results are valuable in many aspects, for example, the development of strain-rate dependent soil constitutive models.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOWARDS DATA-DRIVEN INVERSE DESIGN FOR INTERATOMIC POTENTIALS

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ABSTRACT

The development of an interatomic potential (IP) can be costly and time-consuming. An atomistic simulation must be run for each proposed set of IP parameters to determine the effectiveness of the set in predicting desired properties. Each simulation may be very costly if the property of interest requires consideration of a large domain, e.g. in the case of grain boundary energy, or strength. Here we present a data-driven optimization algorithm and apply it to IP development. The algorithm makes use of a dual neural network (NN) approach, consisting of a forward NN and an optimization NN. The forward NN takes IP parameters as an input and returns an estimate for simple material properties such as bulk modulus or surface energy, playing the role of a surrogate model. It is trained on data automatically generated by tests through the OpenKIM project. A proposed set of IP parameters is then determined by training the optimization NN in tandem with the forward NN, with a goal of matching a set of desired material properties. We evaluate the performance of the algorithm using atomistic simulations. Finally, we present recent work predicting more computationally expensive material properties, such as grain boundary energy or strength, from simpler properties, such as bulk modulus or surface energy, and discuss how these two projects can be combined for IP development.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASPECTS OF CONTINUUM-KINEMATICS-INSPIRED PERIDYNAMICS

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ABSTRACT

Continuum-kinematics-inspired peridynamics (CPD) has been recently proposed [1, 2] as a geometrically exact formulation of peridynamics that is also variationally consistent. Unlike the original peridynamics (PD), CPD can accurately capture the Poisson effect [3]. Due to its nature, CPD does not suffer from zero-energy modes and displacement oscillations. CPD builds upon three types of interactions, namely, one-neighbor interactions, two-neighbor interactions, and three-neighbor interactions. While one-neighbor interactions are equivalent to the bond-based interactions of the original PD formalism, two- and three-neighbor interactions are the basic elements to preserve continuum kinematics exactly.

Moving forward, we elaborate on restrictions on the interaction energies and derive thermodynamically consistent constitutive laws through a Coleman–Noll-like procedure. For three-dimensional elasticity, CPD builds upon three types of interactions that present resistances to changes in length, area, and volume. The isotropic CPD formulation of non-local elasticity, therefore, involves three material constants associated with length, area, and volume. Through localization and linearization, we rigorously establish relationships between the material parameters of CPD and isotropic linear elasticity. It is shown that the three material parameters of CPD reduce to two independent parameters that can be expressed in terms of any pairs of isotropic linear elasticity constants; see [4,5] for two- and three-dimensional analysis. Recent advances and further outlooks of CPD conclude this presentation.

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Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SEQUENTIAL STRATEGY BASED ON NON-DETERMINISTIC KRIGING AND SUBSET SIMULATION FOR OPTIMIZATION OF PROBABILISTIC SYSTEMS WITH MIXED CONTINUOUS AND DISCRETE INPUT VARIABLES

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ABSTRACT

This study proposes a sequential strategy for finding optimum (maximum or minimum) values in probabilistic systems with mixed i.e., a combination of continuous and discrete, input variables while considering aleatory uncertainties. The proposed method aims at exploring local optima with high aleatory uncertainties in addition to the global optimum of the system. Finding optima in complex probabilistic systems, e.g., time-consuming large-scale physical experiments, requires the exploration of both the above-mentioned types of regions to satisfactorily understand the phenomenon within limited resources. Conventional Kriging models employed by past studies for optimization of probabilistic systems with mixed continuous and discrete input variables do not account for the aleatory uncertainty present in the system. The proposed methodology employs a Non-Deterministic Kriging (NDK) approach, which is capable of handling mixed input variables, to include aleatory uncertainties during optimization. NDK method approximates the system mean and associated uncertainties including both epistemic and aleatory uncertainties at unsampled points. A modified version of the expected improvement concept is used to identify the regions of interest during the proposed sequential process. In order to avoid neglecting local optima with high aleatory uncertainties, the subset simulation concept is used to identify the regions where the expected improvement reaches a predefined value. The methodology was applied to a set of analytical examples with different numbers of dimensions to evaluate its efficiency in exploring global optimum and local optima with high aleatory uncertainties. The global optima estimated through the proposed method were compared with the actual global optima of the analytical examples. Error percentages of the estimated global optima for 2, 4, and 8-dimensional analytical cases compared to their actual global optima were 0.68%, 2.6%, and 8.5% respectively. Furthermore, the estimated standard deviation values at the locations of global optima in the analytical examples indicated error percentages of 6%, 7.2%, and 1.8% respectively compared to the actual standard deviations at the respective locations.

Keywords: Sequential strategy, Optimization, Non-Deterministic Kriging, Probabilistic Systems, Mixed input variables

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISION-BASED CABLE DISPLACEMENT MEASUREMENT USING UNI-KLT

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ABSTRACT

Cables are critical structural elements in suspension bridges, and the vibrations of cables caused by factors such as wind and traffic significantly impact the usability of the bridge. Accurate displacement measurement is essential to ensure the safety of cables, but conventional methods are manual and time-consuming. Therefore, automated video-based cable displacement measurement technology is recognized as a crucial tool that can greatly enhance efficiency and safety in industrial settings. Existing research on video-based cable monitoring faces two main challenges. First, users must manually specify the Region of Interest (ROI) for the cable, and if the ROI size is not appropriate, it may lead to a lack of feature points or the extraction of incorrect feature points. Second, due to the cable's shape characteristics, feature points may be lost in the tracking algorithm, resulting in interruptions in the tracking process. In this paper, we propose a video-based cable displacement measurement method using Uni-KLT. It is anticipated that this approach will enhance the safety and efficiency of cable management and maintenance in industrial settings.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTEGRATING PHYSICS-BASED DEEP LEARNING MODELS AND DATA AUGMENTATION FOR HYSTERESIS PREDICTION AND QUANTIFYING MODEL UNCERTAINTY

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[2]University of Toronto

ABSTRACT

Hysteresis is a complex phenomenon referring to a force-displacement relationship changing based on past behavior. Hysteretic behaviors generally involve a wide variability of stiffness, strength, or pinching effects. A plethora of mathematical hysteresis models have been developed, as describing these effects with a universal model is impossible. However, applying a mathematical model to complex hysteresis may lead to model uncertainties due to the potentially inaccurate model form or missing model parameters. On the other hand, the deep learning-based modeling approach has recently attracted attention for its flexibility. Still, the approach faces potential challenges in model uncertainty, mainly due to many model parameters relative to the available data. Therefore, this paper introduces a deep learning approach to hysteresis modeling that significantly reduces the modeling uncertainty. First, the physics-encoded method emulates the mechanism of conventional mathematical hysteresis models to mitigate uncertainties arising from many model parameters to be estimated. We also leverage rate-independent effects for data expansion and apply a physics-informed loss function to ensure a hysteresis model following fundamental physics principles. These strategies provide a robust foundation for accurate hysteresis modeling. The effectiveness of the proposed method in reducing model uncertainties is demonstrated and tested by its application to various hysteresis models, including Bouc-Wen and non-Bouc-Wen models. The proposed approach is expected to provide an effective means to deal with data scarcity in hysteresis modelling of real-world structures.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMAL CONDUCTIVITY OF NANOPAPER FILMS: A CONTINUUM MICROMECHANICS APPROACH

Pedro Miguel Jesus de Sousa Godinho[1]

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ABSTRACT

Nanopaper films made of cellulose nanofibrils are suitable candidates for heat management in several flexible electronics applications [1]. However, natural, as well as technical and technological variability, often results in nanopaper films exhibiting a wide range of thermal properties. Hence, it is important, from an application viewpoint, to develop theoretical models that can guide empirical activities related to such materials (such as their production, research and development, or use), and assist in reducing present uncertainties. With this purpose in mind, the mathematical analogy, in the context of continuum micromechanics and mean-field homogenization, between the conductivity and the elasticity problems [1], serves as starting point for adaptation of a continuum-micromechanics-based theoretical model for the elasticity of paper sheets, to the case of thermal conductivity of nanopaper films [1]. Thereby, large collections of experimental determinations are used to compute volume fractions of crystalline cellulose Iα, crystalline cellulose Iβ, crystalline cellulose II, amorphous cellulose, and water in "mean" cellulose nanofibrils of various origins [2]; while a selection of thermal conductivity properties of the abovementioned constituents of nanofibrils, enables estimation of respective thermal conductivity tensors [1]. It is important to note that the thermal conductivity of hydrated amorphous cellulose (the material that indeed embeds the cellulose crystals), as a function of water content, is not directly available; and that, satisfaction of separation of scales conditions formally excludes self-consistent homogenization of amorphous cellulose and water, leaving only atomistic or sub-atomistic approaches available. As a remedy, we resort to recent findings on the elasticity of cellulose nanofibrils [2] and employ Mori-Tanaka homogenization of cellulose crystals and water, embedded into a dry, amorphous cellulose matrix, to estimate a reliable thermal conductivity tensor for the corresponding composite. Theoretically predicted relationships between porosity and in- as well as out-of-plane thermal conductivity of corresponding nanopaper films, agree well with respective, experimentally determined relationships [1]. Similar agreement is found for cellulose fibrils [1]. The proposed theoretical model gives access to similar models (for instance, for water diffusivity or permeability), and paves the way to a higher level of control in empirical activities related to such materials.

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Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NON-AGEING, LINEAR VISCOELASTICITY OF PAPER SHEETS: A CONTINUUM MICROMECHANICS APPROACH

Pedro Miguel Jesus de Sousa Godinho[1]

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ABSTRACT

Paper materials exhibit time-dependent elastic behaviour [1] that greatly affects their long-term performance, but whose determinants are still poorly understood. To improve this situation, a continuum-micromechanics-based theoretical model for the elasticity of paper sheets, which has recently undergone a comprehensive experimental validation, is herein adapted to deal with the (non-ageing) linear viscoelasticity of such sheets. Thereby, experimental determinations on the viscoelastic properties of lignin (a universal, nanoscopic constituent of paper sheets), indicating that they follow Burgers-like rheological behaviour, and several previously estimated properties of other, multiscale constituents of paper sheets made of mean, softwood-based, unbeaten, chemical pulp fibres, are employed to theoretically predict, in the Laplace-Carson transform domain (based on the “correspondence principle”), homogenized relaxation and creep tensors of a paper sheet made of a typical volume fraction of the aforementioned type of fibres; before the latter tensors are back-transformed into the (physically relevant) time domain, through the famous, multi-precision, Gaver-Wynn-Rho algorithm. The resulting relaxation and creep functions, given in terms of relations between time and deformation, for various initial stress conditions, agree outstandingly well with respective, experimentally determined relations that are currently available [2]. As hemicellulose and amorphous cellulose are both non-crystalline, hydrophilic polymers, they are likely to exhibit viscoelastic properties following Burgers-like (or similar, for instance, power-law-like) rheological behaviour as well; in which case, corresponding, viscoelastic formulations may readily enter the proposed theoretical model and offer an even richer explanation of time-dependent elasticity, not only of paper sheets, but also of its constituent polymer blend, pulp fibres, and cellulose fibrils. The reported results motivate additional developments in viscoelasticity as well as viscoelastoplasticity of paper materials (possibly in the framework of “extended transformation field analysis”), further paving the way to theory-assisted, more accurate and reliable, production, research and development, as well as use of such materials.

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Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELASTOPLASTICITY OF PAPER SHEETS: A CONTINUUM MICROMECHANICS APPROACH

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ABSTRACT

It is a well-known fact that paper materials exhibit elastoplastic behaviour. However, virtually all theoretical models that have been proposed to date are of the macromechanics (or "continuum") type. Hence, the microstructural determinants of elastoplasticity in paper sheets remain elusive. Recently, some progress has been made in this regard, with a proposition based on continuum micromechanics and on extrapolation from elastic concentration relations and from a single fibre parameter covering complex elastoplastic events taking place at the microscopic scale at which fibres appear, being employed to theoretically predict the in-plane, ultimate strength of paper sheets [1]. However, the abovementioned single fibre parameter is a "black box", so to say, having no direct relation with any experimental determinations related to the actual elastoplastic events. Accordingly, we herein go a step further in the process of fully connecting our theoretical model for the in-plane, ultimate strength of paper sheets with physically meaningful experimental determinations, and propose a much more sophisticated theoretical model relying on extensions to Dvorak's classical transformation field analysis that make explicit consideration of plastic strains (in the form of eigenstresses), and which have recently been successfully used to address the elastoplastic behaviour of materials such as bones or rocks. Thereby, we reemploy large collections of experimental determinations that had been used to estimate volume fractions as well as other relevant quantities related to various, multiscale constituents of paper sheets made of softwood-based, unbeaten, chemical pulp fibres; and make use of several parameters related to a non-associated plasticity, to theoretically predict the complete stress-strain curve of the abovementioned variety of paper sheets [2]. Theoretically predicted relations between strain and stress up to ultimate strength agree outstandingly well with respective, experimentally determined curves [2]. These groundbreaking results open the way to more efficient and reliable, sustainable, theory-assisted, production, research and development, as well as use, of such materials.

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Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYBRID MESH TOPOLOGY OPTIMIZATION OF REINFORCED CONCRETE STRUCTURES WITH MOVING TRUSS NODES

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ABSTRACT

Topology optimization (TO) is a design optimization method known to generate high-performing structures with a limited volume of material. TO is particularly powerful because it does not require an initial layout of structural members from the user. Rather, it places material freely inside a defined design space with known forces and boundary conditions, so the method can algorithmically derive highly efficient results. TO has enormous potential for impact in the construction industry because it can help reduce the use of building materials, which produce approximately 10% of greenhouse gasses worldwide [1].

Within existing research on TO for construction, tailoring algorithms specifically to reinforced concrete (RC) design has received considerable attention [2]. RC is an important structural system for research because it is ubiquitous in the construction industry. It can also be easily formed into shaped molds, allowing it to be adapted to complex optimized geometries. A common approach for TO of RC uses continuum elements that are stiff in compression to represent the placement of concrete struts, and truss elements that are stiff in tension to place steel ties. These two components come together to create a truss-like RC structure following the strut-and-tie method [3].

This research will present a new framework for topology optimization of reinforced concrete. Continuum and truss elements will be used together as in [3], but the locations of the nodes of the truss elements will be controlled by design variables, and able to move during the optimization process. Also, SIMP penalization schemes will not be used on the continuum elements, so that their respective design variables can take intermediate values between 0 and 1. These values will be interpreted as varying thickness in the final design, following the Variable Thickness Sheet method. Several numerical design examples will be presented using this new framework, and mid-scale designs (~1 meter spans) will be fabricated and tested to demonstrate their efficacy.

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Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMPORTANCE SAMPLING WITH LANGEVIN DYNAMICS: INTEGRATING OPTIMIZATION AND GEOMETRY FOR ENHANCED RELIABILITY ANALYSIS

Armin Tabandeh[1], Gaofeng Jia[2] and Paolo Gardoni[1]*

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ABSTRACT

Importance Sampling (IS) is a prominent method in the field of reliability analysis for various engineering systems. At its core, IS introduces a biased sampling density, also known as the IS density, to increase the frequency of samples from the failure domain compared to the standard Monte Carlo Simulation. The Euler-Lagrange equation provides the formula for the optimal IS density, yet its dependence on the unknown failure probability makes direct sampling infeasible. A workaround is achieved through indirect sampling by simulating a Markov Chain that is designed to converge to the optimal IS density. Among the available Markov Chain simulation methods, the Hamiltonian Monte Carlo (HMC) algorithm and its subsequent variants stand out. They leverage artificial dynamics to traverse the failure domain more effectively, showing a marked improvement over conventional random-walk algorithms like the Metropolis-Hastings. However, a downside to HMC is its tendency to be time-intensive, especially in high-dimensional reliability problems or those requiring complex model evaluations. We present a novel IS approach that reframes the HMC's inference challenge into an IS density optimization task, drawing parallels with existing optimization-centric algorithms for IS. The proposed approach hinges on the Langevin Equation, which unifies different HMC algorithms into a single general framework. The Langevin Equation describes the behavior of general dynamical systems, wherein the associated governing equation can effectively capture space geometry to rapidly reach and explore the failure domain. By imposing specific conditions on the governing equation, convergence to the optimal IS density is guaranteed, merging geometry and optimization for enhanced performance. The optimal IS density is the steady-state solution of the Fokker-Planck equation, which is intrinsically linked to the Langevin Equation. The proposed approach derives this steady-state solution through optimization. We discuss the optimization formulation and its solution algorithm and illustrate the performance of the proposed approach through benchmark reliability problems.

TOPOLOGY OPTIMIZATION OF IRREGULAR ARCHITECTED MATERIALS WITH TUNABLE RESPONSES USING A VIRTUAL GROWTH RULE

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[2]Peking University

ABSTRACT

Numerous applications demand tunable responses through tailored microscale topologies/geometries of unit cells and macroscale distribution of materials. To achieve these controllable behaviors, notable progress has been made in discovering deterministic architected materials featuring periodic patterns. In this presentation, we explore stochastic and non-periodic architected materials with a continuous design space based on the proposed virtual-growth-based topology optimization methodology. The optimized architected materials demonstrate programmed responses that closely match the desired targets. These optimized materials also ensure microstructural connectivity and offer the flexibility to select building blocks with guaranteed minimal features. Consequently, we leverage such connectivity and minimal features to demonstrate the manufacturability of the optimized designs through 3D printing. Our proposed methodology yields optimized architected materials that precisely realize programmed responses and manufacturing feasibility, which can be beneficial for applications that prioritize structures exemplifying disorderliness, non-uniformity, and heterogeneity.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UTILIZING GENETIC ALGORITHMS FOR OPTIMIZING REACTIVE TRANSPORT MODELING PARAMETERS

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ABSTRACT

The coupled abiotic and biotic processes within the hyporheic zone, where surface water and groundwater mix, play a pivotal role in governing the biogeochemical cycling of carbon, nutrients, and trace elements in streams and wetlands. The intricate hydrological and geochemical dynamics significantly impact these biogeochemical processes, consequently influencing the emission of greenhouse gases (GHGs). Thus, developing a numerical model capable of accurately representing these coupled processes holds considerable implications for the formulation of effective strategies aimed at mitigating global warming. Microbially-induced mineral precipitation and dissolution may promote alterations in the pore structure and affect soil porosity and permeability, thereby further influencing reactive transport processes. Therefore, gaining a comprehensive understanding of the pore structures and alterations in flow parameters during these processes becomes imperative when undertaking the modeling of reactive transport.

To better understand the effect of microstructure changes induced by microbial reactions on transport, we used the Finite Volume Method to simulate biogeochemical processes within a water-saturated soil. The numerical model incorporates sulfur and iron cycles, as well as mineral precipitation and dissolution. First, we studied the influence of alterations in porosity on intrinsic permeability. This analysis employs well-established porosity-permeability relations, such as the Kozeny–Carman equation and Hagen–Poiseuille Law. Next, we compared our numerical results with experimental findings. Given the challenges associated with experimental acquisition of certain parameters, calibration of numerical model parameters was undertaken using statistical methods. Lastly, we constructed a 2D model of the hyporheic zone observed on site. That model incorporates more realistic boundary and initial conditions. Parametric studies were conducted to understand the dominant factors influencing the 2D reactive transport model.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ORIGAMI FOR MECHANICAL HAPTICS

Hanqing Jiang[1]*

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ABSTRACT

The capability of stiffness manipulation for materials and structures is essential for tuning motion, saving energy, and delivering high power. However, high-efficiency in situ stiffness manipulation has not yet been successfully achieved despite many studies from different perspectives. In the first half of this talk, we will present curved origami patterns to accomplish in situ stiffness manipulation covering positive, zero, and negative stiffness by activating predefined creases on one curved origami pattern. This elegant design enables in situ stiffness switching in lightweight and space-saving applications, as demonstrated through three robotic-related components. Then in the second half of this talk, we will present a first-person, human-triggered haptic device enabled by curved origami that allows humans to actively experience touching of objects with various stiffness perceptions from soft to hard and from positive to negative ranges. This new device represents a significant shift away from third-person, machine-triggered, and passive haptics currently in practice. The device is synchronized with the virtual environment by changing its configuration to adapt various interactions by emulating body-centered physical perceptions, including hardness, softness, and sensations of crushing and weightlessness. The high-fidelity stiffness perceptions achieve an unprecedented experience of “what a user sees or is immersed in, is what the user feels or steps on”.

DISCREPANCIES IN STRUCTURAL RELIABILITY: A COMPARATIVE ANALYSIS OF LOAD AND RESISTANCE FACTOR DESIGN AND PROBABILISTIC PERFORMANCE-BASED WIND DESIGN

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ABSTRACT

State-of-the-art probabilistic performance-based wind engineering (PBWE), centered on full reliability analysis, has gained significant attention in the design of engineered building systems over the past few years. The Load and resistance factor design (LRFD), on the other hand, is routinely employed in current design practice and represents a semi-probabilistic approach in which uncertainties are implicitly treated through appropriate partial safety factors. This work is focused on examining apparent discrepancies that arise between the reliabilities targeted by LRFD of wind-excited high-rise building systems and those obtained from explicit reliability analysis. To this end, the reliability of a suite of archetype high-rise buildings, with hypothetical locations of New York and Miami, that conform to current LRFD material and loading codes are carefully studied for a suite of elastic and inelastic component and system-level limit states. The site-specific non-directional wind hazard curve for each archetype is described through a type Ⅰ extreme distribution that is calibrated to the point values suggested in the ASCE 7. Wind directionality is captured through a sector-by-sector approach with coefficients defined from a site-specific analysis of Miami and New York. The dynamic nature of the external wind excitation, including record-to-record variability, is modeled through the adoption of a wind tunnel data-informed proper orthogonal decomposition spectral representation scheme. Reliability analysis was subsequently conducted through the application of advanced stratified sampling in which the nonlinear responses of the structural systems are estimated through time history analysis based on the adoption of recently introduced strain-driven stress resultant dynamic shakedown schemes. In estimating the reliabilities of the archetypes, care is taken to consider a full range of model and loading uncertainties. The results demonstrate that the reliability achieved through explicit reliability analysis is generally lower than those targeted by the LRFD procedure used to design the archetypes. It is suggested that these discrepancies may be traced back to the treatment of wind direction when building-specific wind loads are estimated and used in LRFD. In addition, it is shown that the system-level inelastic limit state of dynamic shakedown generally achieves reliability in line with those suggested by the ASCE 7 for damage that does not lead to sudden or widespread progression of damage. The results of this work have a significant impact on the identification of appropriate target reliabilities for PBWE.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-SPACE INVERSION FOR CO2 STORAGE WITH FLOW AND GEOMECHANICS

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ABSTRACT

Data assimilation (history matching) is an essential step for industrial-scale geological storage operations, as it acts to reduce the uncertainty of flow and geomechanical responses by conditioning to measurements. In traditional model-based data assimilation, model parameters are calibrated to match the simulation results with observations. Data-space inversion (DSI) is a complementary approach in which predictions for quantities of interest, e.g., posterior pressure and saturation, stress along fault planes, are inferred directly, without generating posterior models. This is achieved by using data parameterization on a large number (~1500-2000) of prior simulation results, and posterior sampling with Bayesian inversion conditioned to observations. DSI enables direct forecasting on many challenging cases, which could involve a large range of uncertainties from multiple sources, including multiple scenarios, model error from known and unknown sources, etc. In this work, we develop a new deep-learning-based parameterization using an adversarial autoencoder (AAE) and convolutional long-short term memory networks (convLSTMs) to represent spatio-temporal pressure, CO2 saturation and geomechanical responses. The AAE reduces the dimension of the spatio-temporal data and generates normally distributed latent variables, which are compatible with the Gaussian assumption of ensemble-based data assimilation methods (we apply ensemble smoother with multiple data assimilation in this work). We will present two DSI applications for 3D heterogeneous geomodels characterized by a range of uncertain geological parameters. The DSI results in the first case include predictions of CO2 saturation and pressure fields, at several time steps, using pressure and saturation monitoring well data. In the second case, we apply DSI with pressure and distributed acoustic sensing (DAS) strain monitoring data to predict stress components along fault planes and slip tendency, as well as the cross-fault permeability multiplier and Young's modulus.

USE OF PHASE CHANGE MATERIALS-BASED CEMENTITIOUS COMPOSITES FOR PAVEMENT OVERLAY IN SNOW MELTING APPLICATIONS

Xiaoqiang "Antonio" Ni[1], Brennan Sollenberger[1] and Qingxu "Bill" Jin[1]*

[1]Michigan State University

ABSTRACT

This presentation investigates the application of phase change materials (PCMs) in concrete pavement, demonstrating the snow-melting capability of a double-layer pavement with a top layer of PCM-based overlay on a concrete pavement slab. Various characterization methods were employed to examine the thermal properties of PCMs and their effect on the cementitious materials used in the overlay. The differential scanning calorimetry results indicated that the PCM had a melting point of 0.93℃ and a latent heat capacity of 123.73 J/g, both suitable for low thermal regulation in concrete pavement. Isothermal calorimetry and thermogravimetric analysis showed that PCM incorporation had little effect on the hydration and hydration products of the cementitious materials. The compressive strength of the PCM-based cementitious composites after 28 days of curing was above 30 MPa, meeting concrete pavement application requirements. Three types of concrete pavement slabs were prepared for snow-melting applications: a control slab with regular concrete, a slab with regular concrete and deicing salts, and a double-layer slab with a PCM-based overlay. The double-layer slab exhibited a snow-melting effect similar to that of the slab with deicing salts. These results suggest that PCM-based overlays could eliminate the need for deicing salts, reducing their adverse effects on pavement durability and the surrounding environment.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN MECHANICAL BEHAVIOR MODELING OF GRANULAR BIOMASS MATERIALS

Xuyang Li[1] *and Wencheng Jin**[2]

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ABSTRACT

The U.S. Department of Energy estimates up to 97 billion gallons of biofuels can be produced annually after 2030. This objective is challenged due to significant equipment downtime, which is mainly caused by handling biomass material with variable attributes (e.g., particle size, moisture content) and their complex mechanical behavior. Classical constitutive models often struggle to accurately capture the complex behavior of materials, particularly when attempting to calibrate them based on complete laboratory experiment characterizations for samples with all possible attributes. In this talk, we will present data-driven modeling of the cyclic axial compression and ring-shear stress-strain behavior of granular biomass materials with different moisture contents and mean particle sizes. Laboratory characterization of milled pine samples with a mean particle size of 2, 4, and 6 mm and a moisture content of 0%, 20%, and 40% were carried out. For both the axial compression and the ring shear tests, different levels of compressive stresses were applied. These laboratory data were employed to train two machine learning models: a sequential model using Gated Recurrent Units as the encoder, feed-forward neural nets as the decoder, and an incremental model using feed-forward neural networks. The sequential model uses a sequence of loading history to predict the next step of strain/stress. In contrast, the increment model uses the current state to predict stiffness components and compute stress/strain increment. Both models account for material variations in particle sizes and moisture content. After training, both models demonstrate their capability to accurately predict the mechanical behavior of a diverse set of unseen materials, which augment the existing laboratory data set. They also effectively capture the underlying physics, which involve increased compressibility as moisture content rises and a linear relationship between applied compression and shear strength. This effort established the foundation for comprehensive data-driven constitutive models tailored for unconventional granular materials.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SELF-SENSING CAPABILITY OF CARBON FIBER REINFORCED CEMENTITIOUS COMPOSITE UNDER VARIOUS TEMPERATURES

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ABSTRACT

Self-sensing concrete (Smart concrete) is concrete typically reinforced by conductive admixture (e.g., carbon fiber). The electrical resistivity of smart concrete can response according to different strains and stresses experienced by the material, which makes it feasible to be used as a sensor in concrete structures. In order for the smart concrete to be used as a reliable sensor in real structures, its behavior under practical environmental conditions must be studied. In this study, the carbon fiber reinforced cement composite (CFRCC) with a carbon fiber content ranging from 0.1% to 4% were fabricated and tested in this experiment. The sensing ability of the CFRCC under various temperatures, and mechanical loadings was particularly studied. It was found that the sensing ability of the specimens with a CF content below 1% is much more reliable than that of the specimens with a CF content above 1%. Good reversibility of the strain sensing ability of the samples was found. The temperature test shows that CFRCC has temperature sensing ability from -20°C to 60°C. The results also indicate that the CFRCC exhibits very good sensing abilities of loading, and displacement under low temperature environment. Eventually, the correction factors for temperature effect were estimated and verified.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACCELERATING MULTISCALE SIMULATION WITH MACHINE LEARNING

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ABSTRACT

Multiscale simulation is needed in cases where a single representative constitutive model can not be constructed for the material of interest due to inherent or designed inhomogeneities in the microstructure. Classical multiscale methods rely on subgrid/mesh solves for microstructual samples which are coupled by an equilibrium equation for the full structure. Machine learning via convolution neural networks enable the accurate and efficient encoding of these microstruc- tural response functions. This talk will describe the particular architecture and demonstrate the efficacy of neural networks designed to model the response of microstructural samples. In addition, the models are incorporated in a large-scale simulator that enables material uncertainty quantification and design under uncertainty. Representative boundary value problems will demonstrate the utility of the approach and its correspondence with direct numerical simulation of large-scale structures with microstructural details.

New challenges in instabilities of shell structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INSTABILITY OF A CONFINED STEEL SHELL SUBJECTED TO A SOLID/SOLID EXTERNAL LOADING – EFFECT OF INTERFACE MECHANICAL PROPERTIES.

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ABSTRACT

To ensure the durability in underground facilities, steel pipes are widely used for lining purposes. In several applications as buried pipelines, steel casing in oil and gas production wells, a steel cylinder is confined in soil directly or via an annular grouting within a deformable cavity. This structure is subjected to external loading. Soil pressure and confining medium rigidity are the critical factors to determine the mechanical behavior of the cylindrical steel shell and its possible buckling. In addition, the critical buckling pressure is also influenced by the presence of an interface material between the shell and the confining medium.

The nature of the loading and the confining medium behavior, as well as geometric imperfections have significant effect on the system stability. To study this phenomenon an experimental approach has been used in the laboratory. Buckling test on confined cylindrical shells are carried out. The external loading can be induced by various types of confining media as sand or geotechnical materials. Different data are recorded during the test as the pressure applied on the external face of the interface medium, local strain on different positions of the cylindrical shell and the critical buckling pressure. Hostun S28 sand and cement-based grouting were used as confinement material during the tests.

Different behaviors following confinement media have been observed. A single lobe buckling, characteristic of the buckling of confined cylindrical shells is systematically observed. These experimental results have been compared with numerical simulations to obtain a representative model. Numerical model based on implicit dynamic solver has been developed allowing the access to local pressures and deformations. Using this test-calculation dialog approach for different type of confining media, buckling mechanisms can be studied and the main parameters leading to the single lobe initiation are discussed.

Data-driven methods and research for physical testing in structural engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DAMAGE-SPREAD AND FUTURE CONDITION RATINGS IN PSC-I BRIDGES CONSIDERING COMBINED DAMAGE TYPES AND COMPOUND DETERIORATION

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ABSTRACT

Recently, bridges undergoing rapid aging become increasingly important for the safety, diagnosis, and maintenance of the bridges. Efficient bridge maintenance requires the evaluation of the long-term performance of bridges considering damage propagation and deterioration conditions. Bridge deterioration is influenced by various factors, including freezing and thawing, vehicle loads, and chloride penetration, in the service environment. As most bridges experience two or more different types of damages under multiple complex deterioration factors, effective maintenance measures should account for combined damages and compound deterioration conditions. In this study, a representative PSC-I girder bridge is selected to predict the spread of combined damages in the deterioration conditions and the resulting future condition rating. For this, concrete deterioration models for carbonation and chloride penetration, and structural damage models for damage types, damage characteristics, and damage contributing factors were developed using deep neural network based on past and present climate data, as well as bridge inspection and diagnosis data. To overcome the lack of available data, Monte Carlo simulation were utilized to generate data spanning from the past to the future. By integrating inspection and diagnosis data, climate environment data, and structural damage models, a future condition rating prediction model was developed for the target bridge. The proposed method for damage propagation and condition rating evaluation can effectively predict the current and future conditions of the target bridge, offering valuable insights for bridge maintenance, including estimating required maintenance activities and budgets for future periods.

Keywords: Combined damages, damage-spread prediction, condition rating, deterioration environment

Uncertainty in geomechanical and geochemical processes: Their role on prediction of natural and engineered system behavior
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PERMAFROST-ON-A-CHIP: EXPERIMENTAL STUDY OF THE MOVEMENT OF MICROORGANISMS THROUGH A POROUS MEDIUM UNDER FREEZE/THAW CYCLES

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ABSTRACT

Permafrost, defined as ground that remains frozen for at least two consecutive years, stands as a critical component of Earth's climate system. It serves as a significant terrestrial carbon sink, housing 33% of the global carbon pool within its region, despite representing only 15% of the total soil area worldwide.

Climate-induced permafrost degradation significantly impacts the ecosystem's net carbon balance. This degradation influences various processes, including vegetation dynamics, biogenic activities, and consequent emissions of greenhouse gases like methane (CH4) and carbon dioxide (CO2) into the atmosphere, amplifying global warming.

With our experimental device, we are interested in the descriptions of the processes involved in CH4 and CO2 productions by the interaction of microorganisms and plants, which is also known as Rhizosphere Priming Effect (RPE). The RPE refers to the phenomenon where the presence of plant roots stimulates microbial activity and the turnover of soil organic matter in the surrounding soil, leading to an increase in the decomposition of soil organic matter, which leads to an increase in carbon emissions from the permafrost ecosystem.

The permafrost-on-a-chip system is meticulously designed to investigate the chemotactic motion of Planococcus Halocryophilius, a permafrost bacterium, navigating through a porous medium. This study focuses on understanding how these bacteria move towards nutrients released by plant roots amid the cyclic freeze and thaw. Utilizing confocal microscopy, we track the movement of microorganisms in gradients of both nutrients and temperature, encompassing coexisting liquid water and ice phases within the chip.

To validate this setup's efficacy, we monitor inert particles' transport through the porous medium. These particles are carried by the flow generated by cryosuction resulting from the freezing front. The observations from these experiments are systematically compared against numerical simulations utilizing the Finite Element Method. These simulations aim to comprehend particle transport through advection within the porous medium.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INFLUENCE OF INFILL PATTERNS ON THE MECHANICAL AND FATIGUE CHARACTERISTICS OF FUSED FILAMENT FABRICATED POLYMER PARTS

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ABSTRACT

This research investigates the influence of infill patterns, infill density, and mesh modifiers on the mechanical properties and fatigue characteristics of Tough Polylactic Acid (PLA) components manufactured through fused filament fabrication (FFF). The study focuses on understanding the impact of these process parameters on the tensile and fatigue behaviors of the 3D printed samples.

The experimental setup involved the production of dogbane-shaped test specimens using an Ultimaker 3 FFF 3D printer, with Tough PLA as the filament material. The specimens were subjected to tensile and fatigue testing using servo-hydraulic MTS equipment, and the digital image correlation (DIC) technique was employed to capture full-field deformation measurements. The study also utilized optical micrographs to analyze the surface condition of the samples.

The results revealed that the combination of infill pattern and density significantly affected the tensile strength and Young's modulus of the Tough PLA samples. Specifically, the study found that a 90% infill density, in combination with specific infill patterns and modifiers, yielded superior tensile performance. Furthermore, the inclusion of a mesh modifier was shown to enhance the tensile properties of the specimens, particularly in terms of strain characteristics.

The fatigue characteristics of the 3D printed samples were also investigated, with S-N curves created using stress levels from the testing of specimens. The study demonstrated that the fatigue degradation was proportional to the number of cycles, and certain infill patterns and densities contributed to higher fatigue life for the Tough PLA components.

The fatigue results reveal that specimens lacking modifiers and having a 40% infill density show the highest fatigue life compared to other samples. Nevertheless, a distinct pattern emerges for the 90% infill density, where specimens with a line modifier and grid infill patterns exhibit the third-longest fatigue life. Moreover, DIC images unveiled that samples featuring grid patterns exhibit localized strain near the grip, whereas those with a honeycomb pattern showcase the highest strain concentrated at the center of the gauge length.

Overall, this study contributes to the ongoing efforts to enhance the mechanical performance and fatigue resilience of 3D printed polymers, offering valuable implications for the additive manufacturing industry and related research endeavors.

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SELECTION OF STORM ENSEMBLES CONSISTENT WITH STORM SURGE HAZARD MAPS ACROSS LARGE GEOGRAPHIC REGIONS

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ABSTRACT

The recent destructive hurricane seasons and concerns related to the future influence of climate change have increased the relevance of storm surge hazard estimation when discussing the resilience of coastal communities. The hazard is generally represented as surge inundation probabilities (hazard curves) over a substantially large number of individual locations in the geographical domain of interest. It is assessed by adopting Monte Carlo simulation (MCS), utilizing an ensemble of storm scenarios (along with their occurrence rates) that are representative of the regional climatology. The prediction of the impact of each storm scenario within the MCS is performed by high-fidelity hydrodynamic models. To reduce the overall computational burden, reducing the number of storm scenarios that need to be considered for the hazard estimation is desirable. This is especially true in pre-disaster planning settings when one needs to investigate the impact on the coastal resilience of alternative flood intervention or adaptation measures. Since the estimation needs to be performed separately for each of these measures, the number of storms utilized in the MCS needs to be kept moderately low. This paper investigates the storm selection within this setting to identify a small number of storm scenarios that are consistent with some chosen storm surge hazard maps across large geographic regions. Beyond the scenarios, the occurrence rates are also updated. The identified scenarios can be subsequently utilized as a representative ensemble for the regional hazard estimation. The storm identification framework is established as a two-phase optimization. The inner loop identifies the occurrence rates for a subset of storms, formulating the problem as a linear programming optimization for the sum of absolute deviation of the predicted hazard maps to the target hazard maps. The outer loop searches for the best subset (minimizing the aforementioned sum) with the desired number of storms, adopting a genetic algorithm mixed-integer optimization. It is computationally intractable to consider all the locations in the domain within the overall mixed-integer linear programming formulation, and for this reason, a subset of representative nodes is chosen through cluster analysis. The hazard maps for only these nodes are used in the storm ensemble selection. For clustering, different strategies using correlation between locations based on geospatial information, surge response, or a combination of both are examined. Finally, well-posedness issues are discussed so that the information (across nodes and hazard maps) utilized in the storm selection is adequate for identifying the desired number of storms.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SELF-SENSING CEMENTITIOUS COMPOSITE USING CARBON NANOTUBES

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ABSTRACT

Self-sensing cementitious composite refers to a structural materials that can monitor itself without the need of embedded, attached and/or remote sensors. Compared with conventional structural materials which require additional sensors for monitoring or detection, self-sensing cementitious composite is advantageous in its high sensitivity, higher mechanical properties, and easy installation and maintenance. The research focuses to develop and apply a self-sensing cementitious composite using carbon nanotubes as an alternative for conventional sensors in structural health monitoring. The research examines the effect of carbon nanotubes on the electro-mechanical behavior of a self-sensing cementitious composites. Also, the research proposes new method of self-sensing cementitious composites for better sensing performance.

Small scale phenomena in sustainable & complex materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SORPTIVITY PREDICTION IN SECONDS

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ABSTRACT

The tendency of cementitious systems to absorb and transmit liquid through capillary pores is often characterized by initial sorptivity, which is an important indicator of long-term durability. However, sorptivity measurements, which are based on the continuous mass change of specimens exposed to water, are labor-intensive (up to 6 hours of continuous measurements). In this study, we explain how we may exploit the fundamental surface-wetting characteristics of cementitious systems to estimate their sorptivity in a rapid fashion, i.e., in a matter of few seconds. In a series of 63 unique paste systems of varying w/c ratios (0.4 to 0.8), subject to a range of curing periods (1d to 7d), we establish strong correlations (adjusted R2 ≥ 0.9) between the initial sorptivity (~6 hours) and dynamics of drop spreading (contact angle ~0.5 seconds). These results elucidate novel pathways in rapidly estimating the initial sorptivity and durability of a wide variety of hydrated cementitious matrices.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STREAMLINING CONSTRUCTION INSPECTIONS USING ADVANCED VIDEO ANALYTICS

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ABSTRACT

This project addresses the need for efficient and accurate inspection of Mechanically Stabilized Earth (MSE) wall construction. The current process of construction quality control primarily involves professionals manually visiting the site for progress monitoring or processing large volumes of on-site video data to identify discrepancies in work. This approach is not only time-consuming but often results in significant lag time and delays. This challenge is intensified by the size and complexity of construction projects, leading to potential delays and inconsistent quality across different construction activities. To tackle this issue, this study introduces an approach using time-lapse video analysis. The system utilizes advanced computer vision algorithms and deep learning techniques to automatically detect and flag key activities specific to MSE wall construction. These activities include excavation, compaction, backfilling, laying of straps, and panel installation. By doing so, the system significantly reduces the time inspectors need to spend reviewing video logs to identify construction progress and discrepancies. The introduction of this tool marks an advancement in construction monitoring and quality control. The system’s ability to pinpoint specific activities allows the Department of Transportation staff to efficiently review the construction process, focusing on areas of interest or concern. This not only saves time but also enhances the quality of inspection, potentially leading to cost savings.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF STRAIT TOPOGRAPHY ON THE RISK ASSESSMENT OF EXTREME WIND AND WAVE INDUCED BY TYPHOON USING WRF-ADCIRC-SWAN SIMULATIONS

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ABSTRACT

The coastal structures usually suffer from wave, current, and storm surge hazards induced by typhoons. Parametric typhoon wind field model was commonly adopted due to its high efficiency on estimation of wind hazards in typhoon-prone regions. However, the currently-used typhoon wind field models for wind resistance design of structures in typhoon areas often neglect the influence of the surrounding terrain. This research takes Qiongzhou Strait as an example to describe the influence of channel topography on wind field and wave field. Firstly, the Weather Research and Forecasting (WRF)–Advanced Research WRF (ARW) model is applied to build the precise database of wind fields for historical typhoons that passed through the Qiongzhou Strait. In order to explore the terrain effect on wind field characteristics, the WRF wind field and parametric typhoon field which not considering the influence of topography are calculated to compare the wind speed and wind direction respectively. Then the wave field could be simulated by applying the WRF wind field and the parametric wind field to drive coupled ADCIRC+SWAN. The influence of terrain effect on wave field such as the wave height and wave direction in the research area could be further revealed. It could be concluded that when the terrain changes greatly, the parameter wind field which ignores the influence of terrain would reduce the accuracy of wind and wave field simulation. The influence of topography should be considered in the design of marine structures under terrain significantly changing areas.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZATION OF THE PRESSURIZED SAND DAMPERS RESPONSE WITH THE VAIANA-ROSATI MODEL

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ABSTRACT

This study presents the characterization of the recently developed pressurized sand damper (PSD) in which a steel sphere is moving within a cylindrical tube filled with sand that is under pressure. The experimental results presented in previous studies, revealed that the force output of the PSD is stable, symmetric and nearly velocity-independent; i.e., the PSD is a response modification device that offers a hysteretic response. The component testing at various levels of pressure, stroke amplitude, and cycling frequency revealed an increasing pinching at larger strokes. The fidelity of a newly developed uniaxial phenomenological model, able to accurately simulate hysteretic phenomena in rate-independent systems is discussed in this study. The newly developed Vaiana-Rosati model (VRM) requires only one history variable, and it does not need the solution of a differential equation for the evaluation of the generalized force. The VRM can capture the pronounced pinching of the hysteretic behavior of the PSDs at larger stroke amplitudes when harmonic displacement loading is imposed and it is also capable of producing symmetric force-displacement loops with pinching, when the input motion is a periodic displacement history with successive negative and positive displacement peaks that are not symmetric, or when the input motion is predefined displacement time-histories derived from seismic ground motions. The characterization of the PSD is assessed by comparing the obtained load-displacement loops from the experimental campaign with the VRM when subjected to the aforementioned loading time-histories. The PSDs are designed and built at Southern Methodist University.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNSUPERVISED AI IN STRUCTURAL HEALTH MONITORING FOR LARGE-SCALE STRUCTURES

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ABSTRACT

The advancement of an unsupervised AI algorithm tailored for real-time detection of structural damage signifies a pivotal achievement in the field of structural health monitoring (SHM). The proposed algorithm is developed to discern alterations in a building's dynamic behavior resulting from various environmental forces. Employing a purely data-driven approach, the AI extracts features devoid of direct physical interpretation. These features are subsequently analyzed through a deep support vector domain description, facilitating informed evaluations regarding the structural integrity.

The integration of an attention mechanism within the neural networks is a strategic enhancement, enabling the system to allocate greater analytical weight to critical sensor locations. This focus mitigates the influence of extraneous or superfluous data, thereby sharpening damage detection precision while simultaneously curbing equipment expenses.

Rigorously tested using both a synthetic dataset derived from the ASCE benchmark and empirical data from shake table experiments, the method demonstrates its robustness. Its unsupervised nature, augmented by the attention mechanism, ensures swift and efficient recognition and assessment of structural shifts, relying solely on baseline, undamaged data and a minimized sensor array. Such technological ingenuity heralds a new era for monitoring large-scale edifices, including towering skyscrapers and expansive bridges. It promises a future where the assessment of structural health can sidestep the prohibitive costs and labor demands typically associated with extensive instrumentation or manual examination.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINVENTING DISASTER RESPONSE: INTEGRATED APPROACH FOR ENHANCED 3D DAMAGE SEGMENTATION

Joe Kallas[1] and Rebecca Napolitano[1]*

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ABSTRACT

In the aftermath of disasters, the sheer volume of affected buildings presents a significant challenge in structural health monitoring. A crucial aspect of post-disaster reconnaissance involves the reliable and early detection of damage, along with its accurate quantification, to prioritize recovery efforts and allocate budgets effectively.

This research delves into the application of computer vision and machine learning techniques to reinvent the field of post-disaster damage assessment. It aims to overcome the limitations prevalent in existing literature, which often focuses on small-scale, simple-scale, and single-type damage detection. Our work introduces a comprehensive and robust automated system, capable of detecting and classifying a variety of damage types, levels, and complexities in existing structures within post-disaster areas. This research utilizes photographs taken in the wake of the 2020 Beirut ammonium nitrate explosion to train a machine learning model. These images provide a rich dataset for understanding the multifaceted nature of structural damage in real-world scenarios. The results of this study are promising, showcasing the successful automatic detection and localization of diverse types and levels of building damage, not only from the Beirut explosion but also from other damaged structures sourced from the internet. This demonstrates the method's transferability and applicability to a range of disaster scenarios. A notable innovation of this research is the pioneering use of image segmentation to automate a holistic mapping approach for damaged structures. This method goes beyond mere detection of damaged buildings, allowing for detailed and comprehensive damage assessment. Another groundbreaking aspect is the development of novel methods that leverage image segmentation outcomes to automate the segmentation of 3D point cloud models. This advancement enables precise measurements and quantification of identified damages, including critical parameters such as height, width, length, and others.

These findings hold considerable consequences for advancing the practice of disaster response and recovery. By enhancing the efficiency and reliability of damage assessment, our methods pave the way for faster and more cost-effective recovery efforts. They reduce the need for over-designing emergency interventions and minimize the time required for implementation. This research not only contributes significantly to academic discourse but also holds immense potential for practical applications in disaster response and urban planning. The methodology developed in this study offer a new horizon in structural health monitoring, promising a more resilient future in the face of unforeseen disasters.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

POST-DISASTER DIMENSIONALITY REDUCTION FOR VULNERABILITY ASSESSMENT OF UNREINFORCED MASONRY BUILDINGS

Joe Kallas[1] and Rebecca Napolitano[1]*

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ABSTRACT

This in-depth study investigates the resilience and vulnerability dynamics of unreinforced masonry buildings subjected to blast loads, focusing on data collected from the aftermath of the 2020 Beirut Ammonium Nitrate explosion. It aims to identify key building attributes that significantly influence a building's ability to withstand such loads. The research introduces a novel methodology resulting in significantly enhancing algorithm performance, achieving over 90% accuracy in predicting building resilience in unseen test sets.

The findings of this study are crucial for a wide range of stakeholders, including architects, structural engineers, building restorers, and policymakers involved in disaster preparedness and recovery. The identification of critical attributes affecting building vulnerability forms a foundational basis for developing effective disaster mitigation strategies. This information is invaluable in guiding the refinement of building codes, establishing zoning protocols, and formulating strategic retrofitting plans to strengthen existing structures. The research not only advances scientific understanding of blast-induced building behavior but also provides actionable insights for creating safer, more resilient urban environments. Furthermore, this study contributes to the development of new building regulations and standards aimed at mitigating blast load risks, especially in areas prone to such incidents. The insights gained are pivotal in influencing the design and construction of new buildings, ensuring better preparedness against blast impacts.

In essence, this research represents a leap forward in structural engineering and disaster resilience. It enhances our knowledge of how unreinforced masonry buildings respond to blast loads and offers a practical framework for application. Its value lies in equipping professionals and decision-makers with the tools to create more resilient infrastructure and prepare urban areas for better resistance and recovery from explosive events, ultimately protecting lives and properties.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDRESSING GEOMETRIC AND MATERIAL NONLINEARITIES IN FSI SIMULATIONS WITH THE ALE-SSM FRAMEWORK

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ABSTRACT

This presentation will discuss recent developments in computational fluid-structure interaction (FSI) with the Arbitrary Lagrangian-Eulerian formulation with Skeleton-Based Structural Modeling (ALE-SSM) framework. The development of ALE-SSM was motivated by the need to cost-effectively simulate the interactions of nonlinear structures with fluid motions generated by natural hazards, such as hurricanes and tsunamis. The development of ALE-SSM intends to reduce the computational size of FSI calculations by using force-based line elements to model the structural domain. The significant reduction in the degrees of freedom of the structural domain motivated the use of these elements in ALE-SSM. While this reduction may have a small effect in small-scale FSI problems, in which the fluid domain is expected to govern the computational demand, its influence can be significant in FSI problems that incorporate large-scale structures. ALE-SSM is unique in that it incorporates a geometric model of the physical fluid-structure interface, which is used to establish a reliable communication between the fluid domain and force-based line elements. With the use of a geometric model, the physical structural geometry is well-defined in the coupling domain and discretization of the fluid and structural parts is performed independently. The presentation will discuss the ALE-SSM background and showcase simulations for benchmark FSI problems.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMBINING NONLINEAR SOLVERS WITH TRANSFORMERS FOR ACCELERATING THE SOLUTION OF PARAMETRIC TRANSIENT PROBLEMS

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ABSTRACT

In the field of computational science and engineering, solving nonlinear transient problems still poses a challenging task that often requires significant computational resources. This research introduces a novel methodology that harnesses the power of cutting-edge Temporal Fusion Transformers (TFTs) to accelerate the solution of such problems in multi-query scenarios (i.e. parameterized problems). At each time step, TFT models, renowned for their time series forecasting capabilities, are combined with dimensionality reduction techniques to efficiently generate initial solutions for nonlinear solvers. Specifically, during the training phase, a reduced set of high-fidelity system solutions is obtained by solving the system of differential equations governing the problem for different parameter instances. Then, dimensionality reduction is applied to create a reduced latent space to simplify the representation of the complex system solutions. Subsequently, TFT models are trained for one-step-ahead forecasting in the latent space, utilizing information from previous states to make accurate predictions about future states. The TFTs' predictions are fed back to the system as initial guesses at each time step of the solution algorithm and are then guided towards the exact solutions that satisfy equilibrium using Newton-Raphson (NR) iterations. The basic premise of the proposed idea is that having accurate initial predictions will significantly decrease the number of the costly NR-iterations needed in nonlinear dynamic problems, effectively reducing the solution time. The methodology's effectiveness is demonstrated in numerical applications that involve high nonlinearity, where the TFT-generated initial solutions resulted in a notable reduction in the number of NR-iterations required for solver convergence. This significant enhancement in computational efficiency holds substantial promise, especially in scenarios involving a multitude of analyses and high iteration demands, with wide-ranging applications across computational mechanics and related fields.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL MODELING OF A FIBER REINFORCED POLYMER COMPOSITE WITH INTERLAMINAR THERMOPLASTIC INCLUSIONS

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ABSTRACT

Fiber-reinforced composites (FRC) are lightweight materials that can be engineered to exhibit excellent mechanical performance based on constituent hierarchy. For example, the layered structure of laminated composites provides a large parametric space to customize their anisotropic properties for various design needs. The layered structure, however, makes FRC uniquely susceptible to interlaminar fracture (i.e., delamination). Recent studies [1,2,3] have shown that introducing tough thermoplastic healing agents between individual reinforcing layers can mitigate and reverse delamination damage, thereby endowing composites with a highly attractive self-healing ability. However, the effect of softer thermoplastic inclusions on other mechanical properties (e.g., shear), have not been fully explored.

This presentation discusses a computational approach for investigating the mechanical response of glass-fiber composites containing a 3D printed poly(ethylene-co-methacrylic acid) (EMAA) thermoplastic healing agent. Through nonlinear finite element (FE) modeling, the effect of EMAA inclusions in a 3-point flexure (i.e., short beam shear) geometry are revealed. The numerical models are validated with experimental data, and the study emphasizes the impact of different assumptions, including material constitutive models and boundary conditions, on FE model fidelity. The results show good agreement with experiments, and the investigation provides guidelines on computationally efficient and accurate modeling of FRC materials with interlaminar inclusions. These new findings provide a predictive pathway for composite designers and help lay essential groundwork for future modeling of the coupled damage/healing response.

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Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPPORTUNITIES AND PATHWAYS TO SHAPE ACADEMIC RESEARCH BASED ON INDUSTRY NEEDS

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ABSTRACT

This presentation will focus on opportunities and pathways to shape early career investigator's research agenda based on industry needs. First, the presentation will discuss potential avenues such as the I-CORPS program that investigators can use to develop their ideas by identifying pain points in the industry and find opportunities for collaboration. Once potential opportunities are identified, next, the presentation will deliberate on the nature of the research problems that can be addressed and how academia can contribute. E.g., since both academia and industry use similar tools such as finite element analysis, academia can leverage the time and resources at hand to address industry problems to enable faster or simpler analysis/design. Next, the talk will discuss existing funding opportunities at the state and federal level that can help advance industry informed academic research, such as IUCRC, SBIR, and STTR, and emphasize the importance of having an industry partner/mentor. Finally, the presenter will provide examples from his own experience on navigating the industry-academia collaboration. While the examples will be from the presenter's experiences, it is expected to spur a wider discussion on opportunities for industry collaborations.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MULTISCALE PHASE FIELD FORMULATION FOR CAPTURING THE FRACTURE BEHAVIOR OF RUBBER-LIKE MATERIALS

Prajwal Kammardi Arunachala[1] and Christian Linder[1]*

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ABSTRACT

Given their advantageous attributes such as high stretchability and toughness, rubber-like materials find diverse applications in areas like stretchable electronics, self-actuators, and implantable sensors. Consequently, accurately modeling their fracture behavior becomes crucial for comprehending and designing them resiliently against failures. However, the challenges posed by their multiscale nature, incompressible behavior, and the presence of phenomena like strain-induced crystallization make precise modeling a formidable task. This study seeks to capture the influence of strain-induced crystallization on the fracture behavior of rubber-like materials. We propose a multiscale polymer model integrated with the phase field approach, taking into consideration the effects of the aforementioned microscale phenomenon. At the microscale, non-Gaussian statistics is employed to model chain behavior, accounting for internal energy due to molecular bond distortions and the evolution of crystallites. The non-affine microsphere model, adapted for damaged systems [1], is utilized to bridge deformations across the two scales. At the macroscale, the phase field approach is employed to model damage, assumed to result mainly from the failure of microscale chain segments. The model accommodates the anisotropy induced by crystallite evolution and the enhancement in fracture toughness [2]. The model's performance is validated by comparing simulation results with experimental data.

[1] P.K. Arunachala, S. Abrari Vajari, M. Neuner, C. Linder, A multiscale phase field fracture approach based on the non-affine microsphere model for rubber-like materials, Computer Methods in Applied Mechanics and Engineering 410 (2023): 115982.
[2] P.K. Arunachala, R. Rastak, C. Linder, Energy based fracture initiation criterion for strain-crystallizing rubber-like materials with pre-existing cracks, Journal of the Mechanics and Physics of Solids 157 (2021) 104617.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXAMINING THE INFLUENCE OF FLUID-STRUCTURE INTERACTIONS ON DYNAMIC STALL IN CROSS-FLOW TURBINES UNDER HIGH CONFINEMENT

Rithwik Kandukuri[1], Tony Clay[2], Richard Wiebe[2], Michael Motley[2] and Jennifer Franck[1]*

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[2]*University of Washington*

ABSTRACT

This research looks into the dynamics of fluid-structure interactions in cross-flow turbines, where the axis of rotation is perpendicular to the flow direction. The unique geometry of these turbines, conducive to stacking in arrays, is explored regarding its impact on blade loading. Specifically, we investigate the consequences of high confinement on blade deformations, manifested as pitch and heave variations. Our primary focus lies in examining the dynamic stall process, and understanding how fluid-structure interactions (FSI) affect this phenomenon.

Our study employs a one-way fluid-structure interaction simulation with blade deformations computed through a non-deforming fluids simulation. Mapping these deformations to two-dimensional pitch and heave trajectories, we feed the data back into the fluids solver to observe the changes in loads and performance due to deformations and the intricate dynamics of dynamic stall.

This investigation contributes valuable insights into the subject of fluid-structure interactions in cross-flow turbines, with a specific emphasis on the impact of FSI on dynamic stalls. By studying the permissible loads and deformations in high confinement scenarios, our findings contribute to the design and optimization of these turbines in energy applications.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL MODELING OF PARTICLE INTERACTIONS IN A PRESSURIZED SAND DAMPER SUBJECTED TO CYCLIC LOADING

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[1]Southern Methodist University

ABSTRACT

This Study presents a discrete element method (DEM) numerical model to elucidate mechanical behavior and particle crushing within a pressurized sand damper (PSD) subjected to cyclic loading. PSDs belong to the category of passive control systems capable of dissipating input energy. Energy dissipation in these dampers is predominantly attributed to the shearing forces between sand grains, where these forces outweigh the effects of inertia. PSDs are classified as particle dampers, where pressurized sand particles are placed within a container featuring a movable piston.

Computational simulations of the PSD under different initial pressures and stroke amplitudes were conducted and compared to experimental results. Good agreement was achieved between the DEM model and experimental results for the different cases. Employing elongated, triangle, pyramid, cube, and hexagon particle shapes as well as crushable and uncrushable particles as sand grains revealed that the closest results to the experiments are obtained when using crushable particles. It was observed that reducing the container length for a specific particle shape results in a small increase in contact force. Furthermore, changes in the stroke amplitude, initial pressure, and particle shape had minimal influence on the dynamic force generation. The results show that the majority of crushing occurs in the vicinity of the center of the PSD and within the first loading cycle, mainly in the smallest group size.

This study will enhance the understanding of particle interactions within the innovative pressurized sand damper (PSD). It will also lay the groundwork for future studies on the performance of PSDs and particle dampers made from various materials attached to structures.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE EFFECTS OF BOUNDARY CONDITIONS ON THE AXIAL COMPRESSIVE RESPONSE OF THIN-WALLED CIRCULAR CYLINDRICAL SHELLS

Anindya Karmakar[1], Veera Sundararaghavan Sundararaghavan[1] and Anthony M. Waas[12]*

[1]University of Michigan
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ABSTRACT

Anindya Karmakar (University of Michigan), Veera Sundararaghavan (University of Michigan) and Anthony M. Waas (University of Michigan & Arizona State University)

The problem of predicting the axial response of circular cylindrical thin-walled shells has been a subject of scrutiny for almost a century. The first report that attempted to explain the large discrepancy between the prediction of a so-called classical buckling load against experimental measurements identified unintended geometric deviations of the shell shape as a primary cause. Other possible explanations included material non-linearity of the shell wall material (plastic response) and, to a limited extent, the effects of boundary conditions at the loaded edges. Almroth [1], based on earlier works by Stein [2], used Donnel's shell theory and formulated the boundary value problem and the associated eight possible sets of classical boundary conditions. He used a finite difference approach to solve the resulting equations and presented results for the buckling load for various combinations of the boundary conditions. Since this formulation considered the shell edge boundary conditions, where the load is introduced during the pre-buckling and buckling transition, the results obtained for the buckling load were lower than the classical buckling load, which is based on a solution that assumes an axially invariant shell wall out of plane displacement during the pre-buckling phase. In the present study, we have re-considered the "Almroth" problem with respect to evaluating the effects of the uncertainties in the shell edge boundary conditions by incorporating springs associated with the critical shell edge generalized displacements. First, the governing equations and associated variationally consistent boundary conditions are established using the principle of stationary potential energy. Next, the equations and the associated boundary conditions are decomposed into two sets of boundary value problems corresponding to the pre-buckling phase and the buckling transition. The sets of equations are then solved using a finite difference scheme. It is shown that uncertainties in the shell edge boundary conditions can lead to significant reductions in the corresponding buckling loads. These novel results shed new light on the shell buckling and collapse problem, which may have many implications for the design of thin-walled shell structures.

References
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Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETECTION OF SELECTIVE LEACHING DAMAGE IN BURIED CAST IRON PIPES USING ULTRASONIC WAVE PITCH-CATCH

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ABSTRACT

A methodology to detect selective leaching damage is developed to support aging management of buried cast iron pipes in nuclear power plants. The proposed methodology does not require digging trenches to expose buried pipes and performing nondestructive evaluation (NDE) at a few locations. It uses in situ ultrasonic wave pitch-catch to detect (leaching) damage in a pipe segment. Ultrasonic waves are generated at one end of the pipe segment using piezoelectric actuators and the response is measured using accelerometers at the other end. The time series data recorded by sensors (accelerometers) is processed to compute various damage indices (DIs). A threshold value is defined for each DI to detect damage in pipe segments. It is critical to evaluate the detection accuracy of different DIs for different damage volumes, measurement noise levels, and DI threshold values. This investigation is carried out using simulation experiments. Selective leaching damage is simulated by changing the material properties of a synthetic damage zone in a finite element model of the pipe. Ultrasonic wave pitch-catch is simulated by modeling piezoelectric actuators and sensors. Numerical experiments are conducted to evaluate the detection accuracy of various DIs for several damage volumes, damage shapes, measurement noise levels, and DI threshold values. It is found that all DIs considered in this work could potentially help detect selective leaching in an underground pipe segment. This work provides valuable insights for experimental investigation of in situ selective leaching damage detection.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE DYNAMICS OF CELLULAR PROTEINS DURING CANCER PROGRESSION

Dinesh Katti[1], Sharad Jaswandkar[1], Hanmant Gaikwad[1] and Kalpana Katti[1]*

[1]North Dakota State University

ABSTRACT

The dynamics of three cellular proteins in cancer cells, actin, integrin, and e-cadherin, influence cell mechanobiology and play a vital role in cancer progression. The dynamic remodeling of an actin cytoskeleton is observed in cellular processes such as tumor cell transformation and metastasis. The adhesion protein integrin is essential in adhering cancer cells to the extracellular matrix and mechanotransduction. The adhesion protein e-cadherin is instrumental in cell-cell adhesion, a key aspect of tumor formation. Here, we present the mechanics of these three crucial proteins using steered molecular dynamics simulations and their potential roles in the mechanobiology of breast and prostate cancers during progression at the bone metastasis site. Actin filament polymerization and depolymerization are critical to the cell-cell adhesion observed in tumor formation. Our modeling studies elucidate detailed mechanisms of the cofilin decorations that influence the polymerization and depolymerization of the actins. The integrin studies elucidate the integrin activation mechanism on different surfaces, the adhesion, and the subsequent cell signaling leading to cellular changes. These studies also expound on the mechanisms of integrin deformation under various loading paths. The studies on the e-cadherin-actin complex provide a detailed view of the mechanics of cell-cell adhesion and the cell signaling leading to the e-cadherin junction formation. These studies provide mechanics-based cues to cancer cell progression via the dynamics of the three cellular proteins.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATIONALLY DRIVEN MATERIALS DESIGN OF TISSUE ENGINEERING SCAFFOLDS FOR BIOMECHANICAL TUNING OF FOR BONE REGENERATION AND TESTBEDS OF CANCER BONE METASTASIS

Kalpana Katti[1], Dinesh Katti[1], Krishna Kundu[1], Hanmant Gaikwad[1], Sharad Jaswandkar[1] and Parth Vyas[2]*

[1]North Dakota State University
[2]Sanford Health

ABSTRACT

Achieving optimal mechanical and biological properties in biomaterials is primarily pursued through iterative experimental studies in literature. Here we present a computationally driven materials design of novel tissue engineered scaffolds used for bone tissue regeneration and cancer bone metastasis testbeds. These scaffolds are used to generate engineered bone tissue. In addition, breast cancer and prostate cancer tend to metastasize to bone and at that time the disease is incurable. Testbeds that recapitulate the cancer metastasis are needed so as to enable discovery of new drugs and therapies. To that effect, we have designed bone mimetic scaffolds made of nanoclays that are first seeded with human mesenchymal stem cells (hMSCs) followed by breast and prostate cancer cells. The material of the scaffold is a nanocomposite composed of polymer (polycapralactone), amino acid modified nanoclays and hydroxyapatite mineral mineralized on the modified nanoclay. We use three unnatural amino acids to modify montmorillonite clay (MMT): 5-aminovaleric acid, (±)-2-aminopimelic acid, and 4-(4-Aminophenyl) butyric acid. Molecular dynamics simulations describe the interactions between the modified clay and amino acids. Simultaneously experimental studies are conducted to evaluate mechanical properties structural changes 9XRD) and molecular interactions (FTIR) on the nanocomposite scaffolds. We observe that the interaction energies in the amino acid intercalated nanoclays influence the mechanical properties of the scaffolds with 4-(4-Aminophenyl) butyric acid-modified scaffolds showing the highest compressive strength of the three amino acids. Although the amino acid forms less than 0.2% of the composition of the scaffold, it has a remarkable effect on the mechanical properties. All three composites show good biocompatibility human mesenchymal stem cells (hMSCs). Further, the amino acids within the nanoclays also impact mineralization on scaffolds seeded with hMSCs. The type of amino acid also influenced the amount of mineralization in nanoclays in the scaffolds. Further we seeded human breast cancer cells (MCF-7) on the regenerated bone on the scaffolds seeded with hMSCs. We observe significantly enhanced mineralization in the presence of MCF-7 cells. Thus, a selection of unnatural amino acids directed by simulations, enable design of biomechanically tunable three-dimensional (3D) scaffolds for bone regeneration and bone metastasis cancer testbeds.

TRADITIONAL BUILDING TECHNIQUES AS A GUIDE FOR FUTURE INTERVENTIONS

Stephen Kelley[*1]

[1]*ISCARSAH*

ABSTRACT

Traditional building techniques have come from continuously thriving communities and are based on empirical knowledge which is often tested by historical and social events. These vernacular constructions have been continuously adapted to climate trials, changes in function, and available materials to achieve a desired performance. Inhabitants in earthquake prone regions of the world have often learned to minimize seismic risk in their buildings by developing strengthening techniques within the limitations of the materials that they have available. These so called “seismic cultures” and traditional earthquake resistant techniques have been identified in seismically active regions such as Mediterranean Europe, North Africa, Turkey, Iran, India, the Himalayan Kingdoms, the South Pacific, and Japan. Some of these traditional techniques will be presented and their connect in with modern methods will be illustrated.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEQUENCE-BASED DATA-CONSTRAINED DEEP LEARNING FRAMEWORK TO PREDICT SPIDER DRAGLINE MECHANICAL PROPERTIES

Akash Pandey[1], Wei Chen[1] and Sinan Keten[1]*

[1]Northwestern University

ABSTRACT

We establish a deep-learning framework for describing the mechanical behavior of spider dragline silks to clarify the missing link between the sequence and mechanics of this exceptionally strong and tough biomaterial. The method utilizes sequence and mechanical property data of dragline spider silk as well as enriching descriptors such as residue-level mobility (B-factor) predictions. Our sequence representation captures the relative position, repetitiveness, as well as descriptors of amino acids that serve to physically enrich the model. We obtain high Pearson correlation coefficients (0.76-0.88) for strength, toughness, and other properties, which show that our B-factor based representation outperforms pure sequence-based models or models that use other descriptors. We prove the utility of our framework by identifying influential motifs, and also by demonstrating how the B-factor serves to pinpoint potential mutations that improve strength and toughness, thereby establishing a validated, predictive, and interpretable sequence model for designing sustainable biomaterials with sequence-defined properties.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING OF VORTICES IN STRAIGHT-LINE WIND SIMULATORS

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[1]University of Illinois Urbana Champaign

ABSTRACT

Between 1980 and 2023, severe storms and tropical cyclones (hurricanes) were responsible for 70% ($ 41.4 Billion) of the total annual damage ($59.9 Billion) caused by all the billion-dollar weather and climate-related disasters in the United States. The majority of the extreme wind events constitute the category of nonstationary and non-synoptic winds. However, the investigation of non-stationary (transient) and non-synoptic winds is less explored experimentally in structural wind engineering. This category of winds includes hurricanes, and tornadoes, which are often associated with the presence of vortices such as tornado-like vortices (TSVs) and Meso-vortices (MVs) of a wide range of spatial and time scales. To date, tornado-like vortices have been experimentally recreated using specialized tornado vortex generators only. Very few such vortex generators exist with some questionable limitations, whereas straight-line ABL wind tunnels are in a more mature stage. We are proposing a technique that enables straight-line wind simulators to produce vortices. In the first phase, the efficacy of the proposed idea is investigated using computational fluid dynamics (CFD) simulations. The subsequent phase includes experimental validation of the preliminary CFD findings.

The proposed methodology is based on the philosophy of creating a ‘vortex’ using horizontal shear instability (inspiration drawn from literature on field observations). The implementation of the idea requires a set of louvers and/or barriers to be placed in the fetch of a straight-line wind tunnel. The physical boundaries of the initial CFD simulations are chosen to replicate the boundary layer wind tunnel at the University of Florida. A wall or a barrier is introduced to block nearly half of the flow in the transverse direction and nearly 10% vertically. In addition, pulse inflow is effective in creating a translating vortex in each pulse. Compared with field observations and specialized tornado simulators, the CFD simulations conform well concerning pressure drop and the radial and vertical velocity profiles. In addition, simulations reveal an acceptable degree of repeatability in each pulse.

Subsequently, experiments are performed to validate the preliminary CFD results at the University of Florida wind tunnel. The initial experiments reveal encouraging vortex properties concerning pressure drop and radial and vertical velocity profiles. However, the experiments have a higher degree of variability from pulse to pulse compared to the CFD results. The proposed approach can potentially enhance the capabilities of straight-line wind simulators by integrating the ability to produce realistic characteristics of vortices.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PHASE-FIELD FRAMEWORK TO MODEL CRACK PROPAGATION IN POROELASTIC MEDIA

Salman Khan[1], Chandrasekhar Annavarapu[1] and Antonio Rodríguez-Ferran[2]*

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[2]Universitat Politécnica de Catalunya

ABSTRACT

We propose a hybrid phase-field formulation to simulate crack propagation in poroelastic media. The proposed approach is a three-field formulation (displacements, pressure, and damage as the field variables) with three governing field equations (linear momentum balance, mass balance, and damage evolution). The constitutive response of the medium is modeled as per Biot's theory of linear poroelasticity. The proposed approach extends the hybrid phase-field method of Ambati et al. (Computational Mechanics, 2015; 55(2): 383–405) to poroelastic materials. We demonstrate that, for such materials, a standard implementation of the phase-field method may yield either (a) negative damage, (b) damage larger than 1, and (c) reversible damage. This non-physical behavior is exhibited because the history field variable used in the standard phase-field method was designed for purely mechanical problems and did not include the additional contributions from the product of pressure and volumetric strain. To remedy this issue, we introduce a new history field variable (a pressure history field) to ensure the following constraints on damage: (a) damage is bounded between 0 and 1, (b) damage exhibits monotonic growth, and (c) when pressure is zero, the contributions from the pressure history field vanish. We compare the results obtained using the proposed formulation with the hybrid formulation without the proposed modifications for several benchmark problems. The results demonstrate the advantages of the proposed model for modeling crack propagation in poroelastic materials.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A COUPLED RESERVOIR-GEOMECHANICAL MODELING OF THE SHUAIBA RESERVOIR: A STUDY FOCUSED ON CO2 INJECTION-INDUCED GROUND UPLIFT AND CO2 LEAKAGE

Sikandar Khan[1], Sherif Mahmoud[1] and Abdullatif Al-Shuhail[1]*

[1]King Fahd University of Petroleum and Minerals

ABSTRACT

Carbon dioxide (CO2) sequestration in deep geological reservoirs is a promising mitigation strategy for climate change driven by excessive atmospheric CO2 emissions. In geological CO2 storage, vast quantities of CO2 are introduced into porous reservoirs, sealed by impermeable caprocks. Rapid injection rates can induce pressure increase within the reservoir, leading to structural volumetric expansion. Such pressure surges may also activate pre-existing faults in both the reservoir and caprock, posing risks of CO2 leakage into overlying strata and eventually to the atmosphere. To ensure safe CO2 injection, preliminary geomechanical modeling of the reservoir is imperative. This paper presents a comprehensive coupled reservoir-geomechanical analysis of the Shuaiba reservoir during CO2 injection. Shuaiba's location is optimal for CO2 storage, shielded by the Wasia, Aruma, and Rus Anhydrite geological strata, ensuring protection against potential leakages into the Umm Er Radhuma potable water layer and to the atmosphere. This research examines the CO2 injection-induced ground uplift and Shuaiba reservoir's stability. We have accounted for a fault traversing the reservoir and caprock, and have conducted a CO2 leakage assessment. Our stability evaluation establishes secure injection parameters for the Shuaiba reservoir, guaranteeing CO2 containment without leakage into upper strata or the ambient air.
Keywords: Geomechanical Modeling, CO2 Leakage, Climate Change Mitigation, Global Warming, Ground Uplift, CO2 Sequestration, Stability Analysis

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENERGY HARVESTING THROUGH TEMPERATURE GRADIENT IN SEISMIC INVESTIGATIONS

Sikandar Khan[1], Naveed Iqbal[1] and Khurram Karim Qureshi[1]*

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ABSTRACT

Due to the excessive emission of the greenhouse gases like carbon dioxide in the past few decades, our environment suffers from frequent air pollution that is harmful to all creatures. Our nature contains a lot of unexploited energy that can be used to generate power and preserve the environment. The current research study is focused on providing green energy to the geophone sensors via temperature gradient and using thermoelectrical generator (TEG). Using the temperature gradient as a source of energy for the geophone sensors will cut down the operational and maintenance costs and energy can be harvested whenever there is a temperature gradient. The system will produce the voltage depending on the temperature difference that will charge the geophone's battery. The proposed system was able to effectively charge the geophone's battery at the end of a 24-hour simulation.

Keywords— Thermoelectric generator (TEG), Energy harvesting, Temperature gradient, Geophone sensors.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON NUMERICAL COMPUTATION OF THE BOUNDARY INTEGRAL EQUATIONS

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ABSTRACT

In the literature, the dual reciprocity method (DRM) is one of the famous numerical techniques for solving non-homogeneous PDEs. The idea is to convert the domain integral to an equivalent boundary integral using radial basis functions (RBFs) as interpolation functions. In this work, a connection between the DRM and the dual interpolation boundary face method (DiBFM) has been performed for different types of problems. The DiBFM has two groups of nodes one source node and the other virtual node. In this method, the boundary integrals are treated only on source nodes, and the physical variables are treated by the first-layer interpolation. Further, additional constraint equations are provided through moving least squares (MLS) interpolation for the relationship among the virtual nodes and source nodes. Moreover, the augmented thin plate spline (ATPS) is considered an interpolation technique to interpolate the non-homogeneous term in the desired problem.

The DiBFM is superior in accuracy to the conventional BEM while using interpolation elements instead of conventional discontinuous elements in BEM. Also, the integrand values in DiBFM are attained through curves rather than elements, which eliminates the geometric error. Several numerical experiments are performed for the Poisson equation and compared to the DRM. The claims regarding the supremacy of DiBFM are validated with the numerical results obtained. The extension of the method to higher dimensional domains and to the cases involving unknown functions in the non-homogeneous term are our future interests.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS-INFORMED GRAPH NEURAL NETWORK FOR PREDICTING POWER GENERATION OF WAVE FARMS

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ABSTRACT

To achieve maximum power generation from a wave farm (array of Wave Energy Converters (WECs)), its layout needs to be carefully designed to leverage the hydrodynamic interactions between WECs. To predict the power for WECs with different layouts, Multi-Scattering (MS) has been used. However, MS is computationally intensive, especially as the number of WECs increases, as it requires solving various order of interactions between all WECs for desired accuracy. In this paper, we develop a novel physics-informed graph neural network (GNN) as a surrogate model to efficiently predict the power generation of wave farms. The idea is to model each WEC as a node of a graph and the connection between them as edges of the graph, and then use different interaction blocks to encode multi-scattering within the model. Our approach innovatively incorporates insights from the MS technique to inform the architectural design of our GNN model. Furthermore, the physics of the system is also included in the model via appropriate loss functions, thus ensuring the model learns the fundamental principles that govern the WEC system. We compare results from our model with those from Kriging for 2, 3, 5 and 10 WECs, and the comparison shows that our model can predict the power output with high accuracy and performs significantly better than Kriging.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRAPH NEURAL NETWORKS FOR OPTIMAL POWER FLOW SOLUTIONS UNDER HIGH-DIMENSIONAL UNCERTAINTY

Kamiar Khayambashi[1], Md Abul Hasnat[1] and Negin Alemazkoor[1]*

[1]University of Virginia

ABSTRACT

As climate change propels the shift towards renewable energy and the electrification of demand, power systems are increasingly subjected to uncertainties in generation and consumption. The inherently large size of power systems makes even deterministic Optimal Power Flow (OPF) calculations time-consuming. This challenge is intensified when considering uncertainties, as it requires numerous OPF solutions to account for varied scenarios of uncertainty. Such an iterative approach significantly increases the computational burden, rendering these methods unsuitable for short-term or near-real-time decision-making. Consequently, the development of surrogate models is essential as they replace computationally expensive simulations of the system and facilitate analysis under uncertainty. Among different potential surrogates, Graph Neural Networks (GNNs) have gained increasing attention. Their advantage lies in their spatial reasoning capabilities and adaptability to network variations, such as minor topological changes like line outages. This study introduces a novel GNN-based methodology specifically for solving OPF under the high-dimensional uncertainty of demand and renewable energy injection. The proposed method is validated using standard IEEE test systems. Results show that GNN-based OPF rapidly converges to the optimal solutions, leading to substantial computational time-saving. Moreover, compared to available methods, the proposed GNN-OPF shows significantly improved adaptability to operational changes due to minor topological changes, such as line outages.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGICAL OPTIMIZATION OF METAMATERIALS FOR WAVE CONTROL

Mohamed Habeebulla Khazi[1], Heedong Goh[2] and Loukas F. Kallivokas[2]*

[1]University of Texas at Austin
[2]The University of Texas at Austin

ABSTRACT

We are concerned with the topological optimization of metasurfaces for controlling the propagation of waves. Of particular interest are wave-shielding applications.

We treat the metasurface design problem as a topology optimization problem cast over the metasurface's building block –the unit cell. Specifically, we seek to optimize the shape of a singly-connected cavity embedded within a homogeneous unit cell, in order to satisfy user-defined band gap(s) at prescribed frequency ranges. The band gap could be either directional, i.e., to be realized only at specific directions or angles of illumination, or omnidirectional, i.e., to arrest wave propagation irrespective of the azimuthal incidence.

We design the geometry of the metasurface's unit cell by casting a dispersionconstrained optimization problem over the cell's Brillouin zone. We define a Lagrangian comprising the band gap objective –cast as the vanishing of the group velocity at the gap frequencies– and the unit cell's side-imposed Floquet-Bloch eigenvalue problem. Next, we appeal to the Hellman-Feynman theorem to express the group velocity in terms of the Floquet-Bloch eigenvalues and eigenvectors, and convert the constrained optimization problem into an unconstrained problem amenable to a standard adjoint method. We use finite elements to resolve the first-order optimality conditions with the cavity's nodal coordinates as the inversion variables, use
Reynold's transport theorem to allow for the moving cavity boundary, and deploy specialized elements with C1-continuity on the cavity boundary to ascertain smooth cavity shapes while limiting band-structure artifacts.

We demonstrate the topologically-optimized metasurface band-gap properties with numerical experiments involving wave-shielding applications in 2D.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECOMMENDATIONS FOR NONLINEAR FINITE ELEMENT ANALYSES OF REINFORCED CONCRETE COLUMNS UNDER SEISMIC LOADING UP TO COLLAPSE

Seyed Sasan Khedmatgozar Dolati[1], Adolfo Matamoros[2] and Wassim Ghannoum[2]*

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ABSTRACT

Concrete columns are considered critical elements with respect to the stability of buildings during earthquakes. While experimental investigations of concrete columns subjected to seismic loading have been conducted over the last few decades, gaps still remain in the range of parameters that have been investigated, particularly when it comes to loading history. Nonlinear continuum finite element (FE) models were constructed and calibrated to experimental tests for 21 columns sustaining flexure, flexure-shear and shear degradation followed by axial degradation during cyclic/monotonic loading. The primary objective of this study is to develop FE guidelines for simulating the lateral cyclic behavior of concrete columns with different types of lateral degradation and axial collapse, such that wider parametric studies can be conducted numerically to improve the accuracy of assessment methodologies for such critical columns. Selected columns covered a practical range of axial loads, shear stresses, transverse reinforcement ratios, longitudinal reinforcement ratios, and shear span-to-depth ratios. The modeling process, including the parametric study conducted to calibrate the models, is presented. The crack width, the damage in concrete and reinforcement, the drift at the initiation of axial and lateral strength degradation, and the peak lateral strength of simulated columns are compared with experimental results. Recommendations for selecting FE model parameters are provided. The shear capacities of shear critical columns are compared between models, experiments, and standard equations from ASCE 41-17 and ACI 318-19.

Contributions of high-performing lightweight materials to sustainable development and infrastructure resilience of engineering systems

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENSEMBLE MACHINE LEARNING MODEL TO PREDICT THE COMPRESSIVE STRENGTH OF GEOPOLYMER RECYCLED AGGREGATE CONCRETE

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ABSTRACT

To mitigate the environmental footprint of the construction sector, it is essential to embrace sustainable and eco-friendly approaches. One promising technology is the use of geopolymer recycled aggregate concrete (GRAC), which substitutes fly ash and slag for ordinary Portland cement and replaces natural aggregates with recycled ones sourced from construction and demolition waste. However, the practical adoption of GRAC has been limited, among other things, due to the need for a suitable mix design methodology. This study aims to address this gap by developing a machine learning (ML)-based approach to model the compressive strength (CS) of GRAC. To achieve this, a comprehensive database of GRAC, excluding Portland cement as a binder, was compiled from existing literature, and a tabular generative adversarial network (TGAN) was employed to generate synthetic data to augment the limited training dataset. Eight ensemble ML techniques, including three bagging and five boosting methods, were used to model the CS of GRAC. Extensive analyses were conducted on the developed models to ensure their reliability. The results highlighted the effectiveness of the developed boosting models, including extreme gradient boosting, light gradient boosting, gradient boosting, and categorical gradient boosting regressors, which achieved a mean absolute percentage error of less than 6% in predicting the CS of GRAC. Furthermore, this study identified testing age, natural fine aggregate content, and recycled aggregate ratio to be the three most influential factors affecting the CS of GRAC. Lastly, a graphical user interface was designed to model the CS of GRAC and facilitate practical use.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TRAINING MACHINE LEARNING MODEL WITH METAHEURISTIC ALGORITHMS TO PREDICT THE COMPRESSIVE STRENGTH OF GFRP-CONFINED CIRCULAR CONCRETE SPECIMENS

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ABSTRACT

Over the last 30 years, significant experimental studies have been conducted to understand the characteristics of Glass Fiber-reinforced Polymer Confined-Concrete (GFRP-CC) elements. This research aims to develop a predictive model for the compressive strength of GFRP-CC elements using an extensive database of 319 experimental outcomes from 41 published studies. The developed model considers various parameters influencing the compressive strength of GFRP-CC, including specimen geometry, unconfined concrete strength, GFRP reinforcement ratio, tensile modulus and ultimate strength of GFRP, GFRP reinforcement thickness, and GFRP layer count. Artificial neural networks (ANNs) are widely used in machine learning for accurate predictions, though their structure and parameters are often selected based on prior experience. This study focuses on enhancing ANN performance by integrating metaheuristic algorithms to optimize feedforward backpropagation network parameters. Algorithms like Arithmetic Optimization Algorithm (AOA), African Vultures Optimization Algorithm (AVOA), Flow Direction Algorithm (FDA), Generalized Normal Distribution Optimization (GNDO), and Stochastic Paint Optimizer (SPO) were paired with ANNs. Comparing error metrics shows that the ANN hybridized with the SPO algorithm yields superior accuracy, and a comparative analysis of the five metaheuristic algorithms reveals differences in error percentages. The study employed SHAP-based feature contribution (SHapley Additive exPlanations) and the Olden method to assess key factors affecting GFRP-CC behavior.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING MODEL FOR THE FEXURAL SRENGTH OF 3D-PRINTED FIBER-REINFORCED CONCRETE USING MOUNTAIN GAZELLE OPTIMIZATION ALGORITHM

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ABSTRACT

The escalating demand for concrete in construction has underscored key challenges: rising pollution, augmented energy use, and increasing complexity in concrete structures. Recently introduced, three-dimensional printing (3DP) technology offers a potential solution, enabling the construction industry to navigate these challenges more efficiently. By adopting 3DP for concrete buildings, there is a potential to prevent the necessity for formwork and enable the construction of complex structural geometries. This innovation promises reductions in construction waste, labor costs, and overall project timelines. Simultaneously, when it comes to predicting the strength of 3D-printed fiber-reinforced concrete (3DP-FRC), the Artificial Neural Network (ANN) has demonstrated its efficacy. However, the optimal configuration of ANN remains driven by intuition rather than systematic precision. Therefore, this research endeavors to integrate a meta-heuristic algorithm with a distinct ANN design. The proposed approach in this paper optimizes parameters across a feed-forward backpropagation network, employing the Mountain Gazelle Optimization algorithm in tandem with ANN. The experimental results are subsequently evaluated using R-squared, MSE, RMSE, and MAPE metrics. The refined MGO-ANN approach boasts an impressive R-squared value of 0.97. By providing more accurate data on flexural strength, this predictive model aids in reducing the need for extensive laboratory testing, thereby saving both time and cost. Moreover, the ANN-based model's Graphical User Interface (GUI) was created as a practical tool for estimating the flexural strength of 3DP-FRC for engineering problems.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL-TIME CONCRETE CRACK DETECTION AND SENSING USING AUGMENTED REALITY

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ABSTRACT

Using real-time crack width calculation with Canny edge detection, errors may occur in the crack itself due to factors such as the direction, continuity, and shape of the crack. On the other hand, according to the tests, human factors such as the observer's distance from the crack, the observing angle, and the observer's movement speed also influence the measured crack width. Therefore, this paper will conduct further experiments on human factors through collecting crack width data using Augmented Reality (AR) headsets. If these human factors can be systematically addressed, more accurate data can be obtained, making it easier for observers to use the system and reducing the impact of terrain constraints. Focusing on the error caused by distance and angle, there is a positive correlation between the error and both factors. Additionally, when further investigating the distance, there is an exponential relationship between the pixel unit of the crack and the distance. Various factors contribute to errors in outdoor crack measurements, such as lighting conditions, observation angles, and distance limitations. To initially exclude these factors, this paper focuses on indoor experiments, with the expectation that the findings could be applied to future outdoor observations.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DYNAMIC FORMULATION FOR POTENTIAL OF MEAN FORCE BASED LATTICE ELEMENT METHOD

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ABSTRACT

A potential-of-mean-force (PMF) approach to the Lattice Element Method (LEM) has recently been developed and utilized for simulating the fracture of heterogeneous materials under quasi-static loading [1,2] and linear elastic response of structural systems [3]. In this study we focus on the dynamic nature of natural hazards and aim at adopting the framework developed in [3] to structural dynamics. Molecular Dynamics integration approaches are used within LEM to develop an efficient tool for modeling dynamic responses of buildings with both structural and non-structural components. The minimal contribution of kinetic energy associated with rotational degrees of freedom allows for their removal from the mass matrix through an energy-based condensation and reducing the computational cost. We verify the proposed framework via comparison to benchmark problems and demonstrate its accuracy and efficiency through its application to several structural members and systems subject to different dynamic loadings.

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Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WHAT CAN BE EXPECTED FROM LATTICE MODELLING OF QUASI-BRITTLE MATERIALS?

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ABSTRACT

Lattice modelling of quasi-brittle materials such as concrete is a discrete, mesoscale, description of the material in which constitutive relations are prescribed at a lower scale compared to the scale at which continuum-based constitutive relations are written usually. The meso-structure of the material is represented explicitly. Complex nonlinear responses at the macroscale are obtained, while keeping the constitutive model at the mesoscale simple and less phenomenological compared to macroscale ones. Over the years, such lattice models have become more and more efficient. Prediction capabilities and accuracy of the description of the mechanical response at the global level are, in many cases, better than those obtained with continuum-based models.

The superior capability of lattice approaches has a price: extensive computational cost in structural analyses. Nevertheless, it can be expected that such models will be helpful to produce high-fidelity databases that could be readily used in modern data-driven or coarse-grained approaches. In this lecture, we implement a coarse graining approach based on averaging the equations of conservation to obtain coarse-grained, continuum-based, stress versus strain responses from the Lattice Discrete Particle Model (LDPM). Because stresses and strains are coarse-grained independently, their relationship yields a database of macroscopic continuum responses that can be compared to some existing constitutive models. Here, the isotropic nonlocal damage model is compared with coarse-grained LDPM results.

Two test cases are considered: a dogbone in tension and a three-point-bending notched beam. While very close global responses between LDPM and continuum damage descriptions can be achieved, we show that there are large differences on the local responses. Possible remedies to these differences are investigated to achieve a better continuum-based description of quasi-brittle failure.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN ULTRASONIC IMAGING OF DELAMINATION CAVITIES IN AN ANISOTROPIC COMPOSITE STRUCTURE USING CONVOLUTIONAL NEURAL NETWORK AND LEVEL-SET SPECTRAL ELEMENT METHOD

Boyoung Kim[1], Shashwat Maharjan[1], Fazle Pranto[1], Bruno Guidio[1] and Chanseok Jeong[1]*

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ABSTRACT

This paper introduces a data-driven approach that incorporates a convolutional neural network (CNN) for delamination detection in a 2D plane-strain anisotropic composite structure using ultrasonic measurement data. The spectral element method (SEM), endowed with the explicit time integration and the level-set method, is utilized to accelerate the simulation of the propagation of elastic waves in an orthotropic solid sandwiched by isotropic solids and their interaction with an internal delamination cavity. The level-set method eliminates a need for remeshing per an updated geometry of delamination cavities during the data generation process. We generate training data consisting of binary information (void or non-void elements) of all the elements and the measured wave responses at the sensors.

The CNN learns from these training data sets, and, it provides, based on ultrasonic measurement, an element-wise classification contour map that indicates the probability of each element being a void element. The performance of CNN is assessed using blind test data from ANSYS simulations, explicitly modeling the traction-free boundary of cavities with a fine unstructured mesh.

Numerical results show that our CNN approach can identify the delamination cavities in an anisotropic structure made of aluminum and carbon fiber-reinforced epoxy using ultrasonic measurement. Specifically, in blind tests, the CNN successfully detects delamination cavities, including those with elliptical and non-elliptical shapes of an arbitrary number that the training process has not been exposed to. The presented method can be extended into a more realistic 3D setting and utilized for the ultrasonic nondestructive test of various anisotropic composite structures.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEEP LEARNING BASED STRUCTURAL LOAD IDENTIFICATION

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ABSTRACT

Deep learning is widely and versatilely used in many engineering fields. For civil engineering, deep learning methods are often used to identify structural conditions or damage states from measured responses with/without physical models. Load identification is one of the relevant applications, especially for bridge structures. Traffic loads, a primary concern of bridge structures, can be figured out using Weigh-in-Motion (WIM), which measures the loading magnitude. However, with the assistance of the deep neural network (DNN) model, the loadings on a bridge can be identified using indirect but easily obtainable structural responses, i.e., acceleration, velocity and displacement.

Two simple structures and one real structure are considered to present the development of DNN models and their verifications. Simple structures comprise a cantilever beam and a small-scaled truss bridge. Varying loadings regarding magnitude and location and resulting responses are collected and used for training and validation. For a short-span pedestrian bridge, the number of people and their longitudinal/transverse locations are identified from video recordings. Eventually, the trained models are used to identify loadings on the target structures using only structural responses.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DIMENSIONALITY REDUCTION AS A SURROGATE MODEL FOR HIGH-DIMENSIONAL FORWARD UNCERTAINTY QUANTIFICATION

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ABSTRACT

Uncertainty quantification of physical systems with high-dimensional uncertainties remains challenging, especially when the underlying computational models involve high-fidelity simulations. Surrogate models combined with dimensionality reduction are often used to handle this problem, but the applications can be limited when the input uncertainties are genuinely high-dimensional. To address this challenge, this study presents a framework to construct a stochastic surrogate model from the results of dimensionality reduction in forward uncertainty quantification. The overarching hypothesis is that the high-dimensional input space augmented by the output of a computational model admits a low-dimensional representation. This assumption can be met by numerous uncertainty quantification applications with physics-based computational models. The proposed framework extracts a surrogate model from the results of dimensionality reduction in the augmented input space, which differs from a sequential application of dimensionality reduction followed by surrogate modeling. This feature becomes desirable when the original, non-augmented input space is genuinely high-dimensional. The final product of the proposed framework is a stochastic surrogate model that approximates the original computational model. The proposed approach is demonstrated through uncertainty quantification problems with high-dimensional input uncertainties.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETERMINATION OF THE RELATIVE PERMEABILITY RESPONSE OF WATER-CO2 THROUGH POROMECHANICAL MEASUREMENTS AND ITS VALIDATION

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ABSTRACT

Accurate characterization of the relative permeability curves for water and CO2 is essential for ensuring the efficiency and reliability of injection processes in geologic carbon storage projects. Determination of these curves requires measurements of fluid saturations, pressure differentials, and flow rates of the injection fluids from core flooding experiments. Typically, traditional methods mostly rely on X-ray computed tomography (CT) scanning, which is often constrained by limitations in resolution, difficult accessibility, and complex data analysis. In response to these limitations, Kim et al. (2023) introduced an innovative technique where fluid saturation is determined through poromechanical measurements. This approach involves assessing the undrained response, to determine the degree of saturation of water and CO2. In this study, we conducted a comparative analysis of this method with X-ray CT scanning techniques under controlled laboratory conditions. An advanced experimental setup featuring a high-pressure continuous multiphase flow system was employed, equipped with precise deformation measurement capabilities. The results revealed a strong correlation between the two methods, validating the poromechanical measurement method. More importantly, this research goes beyond validation, by refining the method by assessing the residual saturation. We measure the poromechanical properties during drainage and imbibition and evaluate the residual saturation and hysteresis effects on the relative permeability curves. In summary, this study presents and validates the approach for determining the relative permeability curve by measuring poromechanical properties. This method offers enhanced accuracy in assessing residual saturation and the hysteresis effect, leading to a more comprehensive understanding of multiphase flow behavior. The practicality and applicability of this technique are underscored, demonstrating its critical role in optimizing geoenergy projects.

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4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVERSE CHARACTERIZATION OF DESICCATION-INDUCED SHRINKAGE AND FRACTURE PROPERTIES OF MICROFIBER-REINFORCED BUFFER MATERIALS FOR GEOLOGICAL REPOSITORIES OF NUCLEAR SPENT FUEL

Mohammad Rahmani[1], Abdullah Azzam[1], Yong-Rak Kim[1], Jongwan Eun[2] and Seunghee Kim[2]*

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ABSTRACT

This study presents a multi-step inverse characterization of desiccation-induced shrinkage and fracture of inorganic microfiber-reinforced bentonite clay designed for geological repositories. Bentonite clay is considered a buffer material in engineered barrier systems (EBS) at geological repositories to safely isolate and store canisters filled with radioactive nuclear wastes. The elevated temperature from canisters and confined configuration of bentonite within the EBS leads to mechanically restrained shrinkage and subsequent cracking. This desiccation cracking increases the risk of opening pathways for water infiltration from surrounding rocks, which eventually degrades the canisters [through corrosion] and may incur the dispersion of radioactive matter and the subsequent contamination of the underground environment. Therefore, it is imperative to accurately understand and predict the desiccation behavior of the engineered buffer material. In this study, rheology tests were used to measure the moisture-dependent elastic stiffness of the bentonite clay with and without microfiber, and restrained shrinkage tests were designed and conducted to observe the desiccation-induced deformation and cracking behavior captured by a digital image correlation (DIC) system. A coupled hygro-mechanical finite element model (FEM) with cohesive zone elements was used to simulate shrinkage behavior and desiccation cracking of bentonite clay with and without microfiber. The hygroscopic expansion coefficient by which the shrinkage behavior was characterized was inversely calibrated through an optimization process. The obtained FEM displacement field agreed well with the full-field displacement captured by DIC. To inversely characterize the desiccation cracking through cohesive zone model (CZM) parameters (tensile strength and fracture energy) and address the random cracking associated with restrained shrinkage tests, a novel crack detection algorithm was developed and employed in the optimization process to carefully locate the fracture processing zone (cohesive elements at the crack tip) in FEM. The CZM parameters were iteratively calibrated, so the number of cracks during the desiccation process, crack opening displacements, and their length evolution matched with the experiment. The integrated experimental-computational method in this study can effectively characterize the damage-induced characteristics of bentonite clay with different fiber contents subjected to complex multi-physical conditions of the EBS.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CARBONATION OF ONE-PART ALKALI-ACTIVATED MATERIALS INCORPORATED BY MGO AND CAO: PHASE EVOLUTION, MICROMECHANICAL PROPERTIES, AND SURFACE FREE ENERGY

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ABSTRACT

The distinction in carbonation mechanisms between alkali-activated materials (AAM) and ordinary Portland cement binders causes the direct (C, N)–A–S–H gel matrix decalcification. This study investigated the impact of MgO additive on carbonation mechanisms, stability and polymorphs of carbonation products, and the micromechanical properties of (C, N)–A–S–H gel in two different AAM precursors: 100% slag (high calcium) and 50% slag-50% class F fly ash (low calcium). CO2 curing was conducted in a CO2 incubator with 1% concentration and under atmospheric pressure for up to 56 days. Laboratory tests were conducted in multiple length scales, including pH of pore solution, XRD, TGA, DSC, nanoindentation, and surface tensions in different binder formulations and at various carbonation stages. A noticeable pattern of pH initially dropping and then rising was observed. Integrated XRD-TGA demonstrated the evolution, polymorphism, and amount of calcium carbonates and hydrotalcite phases. Carbonation generally improved the stiffness of the pozzolanic matrix. Moreover, the precipitation of calcium carbonate increased the surface energy of AAM binders. The findings of this study can be used in developing AAM binders and to provide a deeper understating of the carbonation reactions in AAM binders.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION FOR MATERIAL-EXTRUSION ADDITIVE MANUFACTURING WITH LARGE DEPOSITION TO DESIGN FEATURE SIZE RATIOS

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ABSTRACT

Topology Optimization (TO) is a design method that takes advantage of classical optimization methods to converge upon material placements for given objectives and constraints. While the resultant designs are often high performing, materially efficient, and highly complex, this often comes at the cost of manufacturability. However, these costs are mitigated by the development and popularization of Additive Manufacturing (AM) technologies.

While AM significantly increases the manufacturability of TO designs by reducing the number of manufacturing constraints, it is not a panacea. Overhang limitations, feature size limitations, and weak interfilament bond strengths are all examples of key manufacturing constraints that must be addressed in order to produce designs that are not only manufacturable, but also maintain performance fidelity to the original TO design. This work focuses explicitly on the process induced interfilament bond weaknesses and implicitly addresses feature size limitations found in many AM methodologies.

Many AM methodologies employ material deposition techniques that feature a fixed diameter of placed material. This means features sizes must be an integer multiple of said fixed diameter in order to be faithful to the design. Weak interfilament bond strengths is a hallmark of extrusion-based AM methods. These weak bonds result in anisotropic structural behaviors that are difficult to capture in traditional TO methods. Feature size and interfilament bond strength constraints tend to be more pronounced when the material deposition size is large compared to the structural feature size. Examples of this include architected materials and construction-scale 3D printing.

The way that these manufacturing constraints are imposed into the design scheme is via projection-based methods. A geometric primitive that represents a single pass of material placement in the AM scheme is defined such that the weaker regions of the placed material are along the regions of interfilament/material bonding. To allow for directionality of the material placement passes, a ‘library’ of primitives is defined and fine-tuned. To account for feature size limitations, overlapping penalties are imposed on the projections.

This work explores the application of an AM process-aware topology optimization algorithm in cases where the scale of the material deposition size is large relative to the structure scale. A projection-based method is used to implement manufacturing constraints, the Solid Isotropic Material with Penalization (SIMP) methods is used to penalize intermediate densities, and the Method of Moving Asymptotes (MMA) is used as the gradient-based optimizer. The algorithm is demonstrated at different length scales using 2D benchmark examples.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LARGE EDDY SIMULATION OF WIND FLOW OVER OKLAHOMA CITY USING WRF-LES

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ABSTRACT

A high-resolution large eddy simulation (LES) of wind flow over the Oklahoma City downtown area was performed using WRF-LES to explain the effect of the building height on wind flow over the city. A newly released immersed boundary method is used to resolve buildings inside the canopy. It was found that the heights and distribution of the buildings have the greatest impact on the wind flow patterns. The complexity of the flow field mainly depended on the location of buildings relative to each other and their heights. Strong up and downflows were observed in the wake of tall buildings and large-scale coherent eddies between the low-rise buildings. It was found that high-rise buildings had the highest impact on the urban wind patterns. Other characteristics of urban canopy flow, such as wind shadows and channeling effects, are also successfully captured by the WRF-LES simulation.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZATION OF FATIGUE DAMAGE IN CONCRETE: AN EXPERIMENTAL STUDY ON MECHANISMS AND PARAMETERS INFLUENCING FATIGUE LIFE

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ABSTRACT

Concrete is a heterogeneous quasi-brittle material used in the construction of projects including highway pavements and bridges which are subjected to fatigue loading. The micromechanics of fracture and damage evolution in concrete under fatigue loading is a complex and distinct process and stands to be an open problem. Under monotonic loading, it is well understood that the cluster of multi-scale cracks ahead of a dominant crack known as the fracture process zone (FPZ) is responsible for the size-effect phenomenon and the occurrence of various toughening mechanisms including crack bridging, crack tip blunting, and crack deflection [1]. Since the constituents of concrete vary from nano to millimeter length scales, the fatigue failure is a manifestation of progressive damage from micro-scale to macro-scale [2]. With the advancement in micro-level sensing techniques, through imaging and acoustic emissions, it is possible to understand the various microstructural changes taking place in the material when subjected to fatigue loading.

This research focuses on studying the crack growth mechanisms of concrete at micro and macro scales through an experimental investigation of different-sized concrete specimens using digital imaging and acoustic emission sensing techniques. Various parameters are included in the fatigue loading including stress ratio and frequency besides specimen size and notch-to-depth ratio. The behavior of the specimens is captured through non-contact digital images, acoustic emission sensors, LVDT and COD gages.

It is shown that the failure mechanisms in concrete under fatigue loading are markedly different from those under monotonic loading. Microcracks dissipating lower to higher energy are observed continuously during the pre-peak and post-peak softening stage under monotonic loading. However, microcracks dissipating lower energy only are seen during most of the fatigue life with the higher energy cracks seen only close to final failure. These observations have a significant bearing on the modeling of fatigue damage and estimation of the residual life of concrete structures.

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Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONSERVATISM IN THE STRUCTURAL DESIGN PROCESS ASSOCIATED WITH ASSUMING DYNAMIC LOADS ARE STATIC

J. Brent Knight[*1]

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ABSTRACT

Assuming that dynamic loads are static in the design of structures is a long-standing engineering practice. The assumption is conservative for hardware that will have limited exposure to the specified dynamic environment and a fatigue failure is not a concern. This is the case for most space flight hardware. Once, out of the Earth's atmosphere significant vibrations are non-existent for most hardware, and, therefore, vibratory cycles are limited. Mass is, and has always been, a concern with respect to flight hardware design. How much unnecessary mass, due to the subject assumption, may be in structural designs was questioned and numerous tests have been performed to answer that. Results of those tests are reported in this presentation. These results illuminate the potential gain, mass savings, via developing a physics based quick turnaround methodology to design structures for dynamic environments.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TIME-DEPENDENT RELIABILITY ANALYSIS OF WATER PIPELINES USING BAYESIAN SUBSET SIMULATION

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[1]University of Waterloo

ABSTRACT

Human beings adopted a settled life in the Neolithic age when the agricultural revolution occurred. Thenceforward, access to water has been one of the most important parameters of settled life. Even today's modern societies are no less vulnerable to water shortages than before. In this context, water distribution networks are one of the indispensable components of modern life and cities. Therefore, many academic studies have focused on measuring the system reliability of existing water pipelines. In this view, we aim to develop a time-dependent reliability analysis framework for the entire pipeline system subjected to external corrosion with uncertainties. The time-dependent corrosion is modeled using a power law which considers growth of maximum defect depth and defect length whose occurrence is modeled by a Poisson’s process. The system reliability of pipelines is estimated based on serviceability and ultimate limit state functions such as leakage, burst, deflection, collapse, bending, etc. The Monte Carlo simulation is one of the viable tools to estimate time-dependent failure probability. However, due to large computational time, it is not useful in practical scenarios. Therefore, in this study, we propose a Bayesian enhanced subset simulation to estimate the probability of failure with the aim of reducing computational time. Finally, a sensitivity analysis is carried out to examine the factors influencing the probability of failure of the pipelines.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FIBER-REINFORCED CONSTITUTIVE MODEL FOR EARTHEN MATERIAL IN PARTIALLY SATURATED CONDITIONS

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ABSTRACT

A new elasto-plastic constitutive model for fiber-reinforced materials is developed. The model considers the effect of distributed fibers embedded in a matrix. The effect of the tensile stresses in the fibers is integrated numerically over possible orientations to convert it into a homogenized composite material stress. The fiber model considers both the degradation of the cohesive bond due to fiber-matrix interface mechanism, the elasto-plastic behavior of the fibers and their ultimate strength. Fiber model is coupled with the constitutive model of the soil matrix to obtain the constitutive model of fiber reinforced soil. Additionally, the soil model is embedded in a partially saturated framework. A mixed finite element formulation is employed to account for the coupling of the solid skeleton and pore fluid. The dry case and the fully saturated case are obtained as special cases of the partially saturated formulation. A finite element code is developed in Matlab to implement the coupled formulation. The finite element code for the soil with no fibers is verified with several numerical examples with known solutions from literature. Furthermore, the fiber-reinforced material is used to investigate the behavior of various structural elements in partially saturated conditions and loading, with the overall goal of improving the mechanical behavior of this material.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRONTAL PERSPECTIVE TRANSFORMATION WITH AN ARBITRARY VIEW IMAGE FOR ABSTRACT MODEL OF A BRIDGE

Eunbyul Koh[1] and Robin Eunju Kim[2]*

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ABSTRACT

Maintaining aging infrastructure requires a cost-effective and straightforward methodology for effectively assessing its stability and reliability. In most cases, the model-based structural health monitoring uses a Finite Element Models (FEM) built based on the construction design. Such models may provide predictive capability when calibrated with in-service response of the structure. However, utilizing such a sophisticated FEM may be economically inefficient in some cases, especially when on-site understanding of structural conditions is of interest. In response to these limitations, many researchers proposed non contact sensor-based monitoring strategies attempting live inspections. Vision and laser scanning sensors have emerged as potential tools, reshaping the landscape of structural assessment method. For instance, laser scanners are implemented to obtain 3D point cloud data by scanning an object. Using scanned point cloud data, FEM can be achieved by segmenting groups of point clouds. However, to achieve a certain resolution, increased scanning time is required for data processing. In addition, vision sensors are used to calibrate FEM by tracking dynamic responses of the structure. However, those approaches still require a priori model of the structure limiting the live survey. Therefore, in this research, single image-based modeling approach is proposed which constructs abstracted FEM without having to have a prior model. Focusing on bridges, proposed framework develops an abstract model that possesses fundamental characteristics of the structure. Herein, frontal perspective transformation is applied by predicting camera positions from a single image and transforming side-captured images into frontal perspectives. The proposed methodology is validated through both lab-scale and real-world structures. Then, to create a FEM, frontal perspective images undergo element-wise segmentation, resulting in a realistic three-dimensional representation of the bridge morphology. By concentrating on bridges, this study introduces a focused and targeted approach, forecasting camera positions based on the relationship between the target and camera positions in a single image. The proposed approach not only solves geographical problems when photographing a bridge from the side of the structure, but also creates and models the shape of the 3D structure based on the images. The resulting three-dimensional model with detailed morphology represents a promising advancement for efficient, economical and accurate structural evaluation in structural maintenance. This study represents a paradigm shift in FEM methodology for structural health monitoring.

Data-driven methods and research for physical testing in structural engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DATA-DRIVEN APPROACH TO HOLLOW STRUCTURAL SECTION COLUMN DESIGN

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ABSTRACT

In the field of structural engineering, there is a growing interest in integrating data-driven design tools to optimize designs. This study aims to enhance the application of data analytics in structural design by focusing on hollow section columns as a test case. First, the necessity of advanced data analytics is shown by demonstrating how simple interpolation approaches are not sufficient for the complex data sets used in structural engineering. Next, this study demonstrates how advanced data analytics can be used to augment the structural design process.

This study compiled a comprehensive database of experimental and numerical research on square and rectangular hollow section columns. Both conventional interpolation and advanced machine learning techniques were utilized to estimate buckling strength. To evaluate the accuracy of predictions from the proposed data-driven model, comparisons were made with current design standards such as AISC 360 and Eurocode 3. Two main aspects were considered for the hollow section database: (1) high-strength steel, which presents challenges due to overly conservative predictions based on equations designed for normal-strength steel, and (2) formation process where those produced from cold-working are often unconservatively predicted by current design specifications. The study seeks to address these challenges by promoting the practical adoption of data-driven structural design methods. This involves providing open-source execution tools and codes to bridge the gap in utilizing data analytics advancements within the field of structural engineering. Furthermore, the paper highlights practical applications of the developed data-driven methods to encourage structural designers and fabricators to embrace data-guided approaches in their design processes.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BUCKLING DETECTION OF PROFILED STEEL DECK USING INNOVATIVE MEASUREMENT TECHNIQUES

Hyeyoung Koh[1], Gowshikan Arulananthan[1], Nate Opperman[1], Jesse Hampton[1] and Hannah Blum[1]*

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ABSTRACT

The structural behavior of thin-walled steel structures is complex due to their susceptibility to local buckling, which poses significant challenges in accurately measuring and analyzing their deformed configurations. While traditional strain measurement techniques, such as electrical strain gauges, have been utilized to evaluate structural deformations, their discrete point strain readings limit the comprehensive capture of the complex deformation shapes of structures. This study proposes a novel approach, distributed fiber optic sensing, to detect and analyze the buckling behavior in steel members. Strain measurements from distributed fiber optic sensing can enable a more precise assessment of the complex buckling behavior of steel members including quantifying global and local buckling.

This study aims to provide detailed guidance on implementing fiber optic sensing for assessing steel structural behaviors, with a specific focus on the application of this approach to roof deck members that are corrugated thin-walled steel sheets widely used to support the roof or flooring of buildings. The experimental testing involved loading the deck to failure inside a structural vacuum box chamber, designed to provide uniform loading across the entire roof surface. Various measurement methods for strains and deformations were employed during testing, including fiber optic sensing, optical tracking cameras, and electrical strain gauges. Fiber optic cables were used to measure distributed strains on the top and bottom flanges of the deck profile across the entire span in the longitudinal direction, as well as on the top flanges in the transverse direction. The distributed strain data obtained from fiber optic cables were compared with both the strain gauge data at discrete points and shell finite element analysis results. Additionally, optical tracking cameras were installed inside the vacuum box chamber on the underside of the deck to capture the deck deformations. This presentation focuses on the results of the experiment and the data analysis of distributed strain from the fiber optic sensing. The outcomes of this study contribute to an enhanced understanding of advanced measurement techniques for structural testing and introduce an innovative solution for accurate deformation and buckling detection in thin steel members.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IDENTIFICATION OF VERTICAL DYNAMIC PARAMETERS FROM EARTHQUAKE DATA RECORDED IN A HIGH-RISE

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ABSTRACT

System identification techniques are applied to vertical-component acceleration data recorded in a high-rise building to measure vertical-mode dynamic parameters that are useful to structural design and health monitoring. The dynamic parameters are obtained from bandpass filtered acceleration data and from impulse response functions computed using interferometric techniques. The vertical-polarity accelerations are from local earthquake data recorded on nearly every floor of a 52-story moment-and-brace frame building in downtown Los Angeles. The observations are from triaxial MEMS sensors that are part of the Community Seismic Network, and the earthquakes examined here include the 2019 M7.1 Ridgecrest, CA; 2020 M4.2 Pacoima, CA; and 2020 M4.5 El Monte, CA. The system identification results indicate that the frequency of the first vertical mode is about 1.8 Hz and that this frequency is amplitude dependent, as indicated by the range of earthquake excitations. The second vertical mode is identified as ~3.4 Hz. Beating is observed for the first vertical mode that may be due to close coupling of modes associated with compressional and extensional motions in the vertical direction resulting from changes in vertical stiffness between interior core and exterior columns. This phenomenon is further examined in a two-degree-of-freedom system representing the building, which can explain similar beating effects around the first vertical mode of 1.8 Hz. The results highlight the value of high spatial density triaxial sensor deployments to record vertical dynamic behavior in tracking vertical forces floor levels that may contain signs of strength degradations in connections due to multiple earthquakes or long-term cyclical loading.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BRIDGE INSPECTION BASED ON COMPUTER VISION AND ROBOTICS

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ABSTRACT

The number of Bridges in service is huge and the maintenance work is arduous. Currently, most of the bridge inspection technology is mainly dependent on manual inspection with low efficiency, high subjective, and far from meeting the needs of engineering practice. Deep integration with artificial intelligence, robots and other emerging technologies to achieve the digitization, intelligence and information of bridge operation and maintenance is an inevitable trend. Focusing on the above issues, we have developed a UAV-based technique for structural surface defect detection, a robotic technique applicable to the internal inspection of bridge towers, concrete/steel box girders, and other structures, and developed a computer vision-based measurement technology for structural vibration, cable force. The research results have been applied to the operation and maintenance of many bridges in practice.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INPUT-STATE-PARAMETER ESTIMATION USING PHYSICS-INFORMED NEURAL NETWORKS AUGMENTED WITH SPECTRAL INFORMATION OF NATURAL HAZARDS-INDUCED EXCITATION

Antonina Kosikova[1] and Andrew Smyth[1]*

[1]Columbia University

ABSTRACT

Traditional model updating techniques for parameter estimation often require extensive knowledge of the system and the excitation to which it is subjected. Determining the time-varying forces applied to a system is particularly challenging, and while methods such as modal hammer testing and operational modal analysis can update our understanding of a system's structural characteristics, they also have limitations. Modal analysis may not capture all the dynamics accurately, and hammer testing (or other moving excitation testing) often involves laborious on-site work. To address these challenges, this study introduces a method for estimating input forces, system states, and updating system parameters by integrating Physics-Informed Neural Networks (PINNs) with spectral information derived from hazardous natural phenomena such as thunderstorms and earthquakes. These events are well studied as they can produce strong system responses and can lead to structural damage. This paper suggests using available knowledge of the spectral characteristics of these events to create a surrogate for the forces applied to a monitored system. The approach leverages the conventional advantages of PINNs, such as their ability to encode underlying physical laws in the learning process, and enhances them by integrating spectral information, providing additional constraints for the estimation of the input. This formulation helps reduce the uncertainty of the predicted forces and states, leading to more robust system identification in the presence of unknown input forces. The versatility of the method is demonstrated through its application to both a linear system excited by the strong winds of a thunderstorm and a nonlinear system subjected to an earthquake.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF BEAMS' CROSS-SECTIONAL PROPERTIES CONSIDERING TORSIONAL AND WARPING BEHAVIOR

Christos Kostopoulos[1], Ameer Marzok[1] and Haim Waisman[1]*

[1]Columbia University

ABSTRACT

This paper introduces a novel efficient topology optimization methodology for beams' torsion using the warping function formulation. The finite element method is used to discretize the cross-section of the beam and an efficient gradient-based optimization problem is formulated to optimize the relevant parameters corresponding to the torsion and warping constants of the beam. As a result, for the first time, one can optimize a beam for problems where the warping behavior is dominant. Density-based optimization is defined where the SIMP approach is utilized to penalize intermediate element densities. A key challenge of the optimization that arises in the warping function framework is the so-called, updating right-hand side problem. That is, the forcing vector varies during the optimization as it depends on the cross-section boundaries, which are functions of the updating topology. To this end, an efficient differentiable boundary recognition algorithm is proposed. The methodology is applied to design beam cross-sections in which both torsion and warping constants are of interest. While intuitive topologies are obtained in the case of optimized torsion constant, this is not the case for the warping constant. The latter shows unique material distributions and a special dependence on the allowable material density.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHASE QUANTIFICATION OF ANHYDROUS CSA CEMENTS: A COMBINED X-RAY DIFFRACTION AND RAMAN IMAGING APPROACH

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ABSTRACT

Calcium Sulfoaluminate (CSA) cement, also known as ye'elimite-containing cements, are popular for their special properties such as rapid setting, shrinkage compensation, and high early-age strength. They are increasingly used in specialized applications such as the rapid repair and replacement of concrete pavements on highways and airport runways. However, the complexity of these cements is due to the presence of numerous phase assemblages, some of which incorporate foreign ions into their crystal structure and display polymorphism. Accurately quantifying these phases and their respective polymorphs is crucial for predicting the performance of CSA cements. Nevertheless, quantifying anhydrous CSA cements via X-ray diffraction-based Rietveld refinement remains challenging due to the presence of overlapping peaks, polymorphs, and preferred orientation. To address this issue, we introduce a new approach that combines high-resolution large-area Raman imaging (5mm x 5mm, 250,000 pixels, with 10 μm/pixel resolution) and XRD Rietveld analysis. Our results reveal that the two methods are highly complementary in the initial phase identification for these anhydrous CSA systems. Furthermore, our quantitative analysis shows a strong correlation (R2 > 0.98) and agreement between the two independent methods, with a variation of less than 4 wt.%., thereby adding confidence and reliability to the phase assemblage obtained using this dual technique approach.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL STUDY OF BROKEN WAVE ATTENUATION AND LOAD MITIGATION BY MANGROVE FORESTS OF VARYING CONFIGURATION AND DENSITY

Vasileios Kotzamanis[1] and Dimitrios Kalliontzis[1]*

[1]University of Houston

ABSTRACT

Significant field evidence shows that mangrove forests provide a green line of defense for coastal structures against hurricane storm surges and tsunamis by attenuating the incident waves. The focus of this experimental study is to understand and correlate the shielding effect created by mangrove forests of different densities and configurations against hurricane- and tsunami-like broken waves. The experiments were performed in the wave flume facility at the University of Houston that includes a piston type wave generator and a beach profile with a 1:8 slope. The mangrove forest was modeled with a set of prototype mangrove trees detailed using computer-aided design and fabricated at a 1:19.2 scale using a 3D printing approach. The experimental setup also included a rigid wall instrumented with a series of pressure gauges, which was placed downstream of the mangroves. The shielding effect was evaluated by comparing reductions in the free surface elevation and impulsive forces exerted on the rigid wall. It was observed that mangrove configurations of increased density resulted in reduced impulsive forces and that mangrove shielding was most effective against shorter waves.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT STOCHASTIC RESPONSE DETERMINATION OF NONLINEAR STRUCTURAL SYSTEMS: AN EXTRAPOLATION APPROACH WITHIN THE WIENER PATH INTEGRAL TECHNIQUE

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ABSTRACT

The Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear dynamical systems treats the system response joint transition probability density function (PDF) as a functional integral over the space of all possible paths connecting the initial and the final states of the response vector [1]. Further, the functional integral is evaluated, ordinarily, by considering the contribution only of the most probable path. This corresponds to an extremum of the functional integrand, and is determined by solving a functional minimization problem that takes the form of a deterministic boundary value problem (BVP) [2]. This BVP corresponds to a specific grid point of the response PDF domain. Remarkably, the BVPs corresponding to two neighboring grid points not only share the same equations, but also the boundary conditions differ only slightly. This unique aspect of the technique is exploited herein.

Specifically, it is shown that solution of a BVP and determination of the response PDF value at a specific grid point can be used for extrapolating and estimating efficiently the PDF values at neighboring points without the need for considering additional BVPs. Further, the proposed extrapolation approach is extended to account also for the temporal dimension. This is done by leveraging the information inherent in the time-history of the most probable path. Overall, the herein developed extrapolation approach enhances significantly the computational efficiency of the WPI technique without, practically, affecting the associated degree of accuracy. Notably, it is demonstrated that, for a given degree of accuracy, the extrapolation approach is several orders of magnitude more efficient than both a brute-force implementation of the WPI technique and a standard Monte Carlo simulation (MCS) solution scheme in determining the nonlinear system non-stationary response joint PDF.

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Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SURROGATE MODELS FOR ESTIMATING EARTHQUAKE-INDUCED DOWNTIME OF BUILDINGS IN REGIONAL RISK ASSESSMENT

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ABSTRACT

Post-earthquake recovery of buildings plays an integral role in community resilience. While existing regional risk models have often concentrated on quantifying earthquake-induced direct economic loss and repair time as primary risk metrics, the quantification of earthquake-induced downtime in building portfolios involves various sources of uncertainty (e.g., delays due to impeding factors) and remains underexplored. This study proposes a surrogate model for estimating earthquake-induced downtime of building portfolios by leveraging building-level recovery assessment results obtained from TREADS (Tool for Recovery Estimation And Downtime Simulation). Specifically, the total downtime includes the time for mobilizing resources after an earthquake (i.e., impeding factor delays) and conducting necessary repairs. Using these results, limit state functions, conditioned on an earthquake ground motion intensity measure, are developed based on a building's post-earthquake usability status, (i.e., irreparable, shelter-in-place, and functional recovery). For irreparable buildings, downtime is taken as the building replacement time, considering the probability distribution of demolition and reconstruction times. For repairable buildings, downtime is computed at two distinct recovery states, (i.e., shelter-in-place, and functional recovery). At each recovery state, distinct surrogate models, employing Gaussian Mixture Models, are developed for impeding factor delays and repair times. The proposed framework is implemented in a series of modern high-rise reinforced concrete shear wall buildings ranging from eight to 24 stories which are subjected to ground motion records at five different intensity levels. This research provides valuable insights into incorporating building recovery estimates in regional risk models, which can inform policy decisions toward accelerating post-earthquake regional recovery and enhancing resilience.

INVESTIGATING CONVEXITY-ENFORCED DEEP REINFORCEMENT LEARNING ALGORITHMS FOR POMDPS

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ABSTRACT

Inspection and Maintenance (I&M) planning problems are characterized by high uncertainties regarding the system state, many parameters, and interactions, including reliability and safety constraints. These characteristics make I&M planning notoriously difficult. In recent years, researchers have started to employ Deep Reinforcement Learning (DRL) to I&M planning [e.g., 1]. DRL has been widely applied to solve complex problems, such as games like Chess and Go, or protein folding. However, most of these problems concern perfectly observable domains, although recent studies have also started focusing on partially observable domains. On the other hand, many theoretical advancements have been made in RL, which have been used in dynamic programming [2] to tackle partially observable domains. Nevertheless, thus far, little to no work has been performed to apply these concepts also to DRL.

In this work, we explore theory-guided DRL. Specifically, we present a novel approach to enforce the convex property of the value function in the belief space during training of the neural network. We hypothesize that the proposed approach can outperform existing DRL algorithms by showing quicker convergence due to restrictions of the search space, and in applications to out-of-distribution domains due to well-behaved extrapolation. We evaluate our approach on a toy computer game and compare it to a DRL approach without the enforced convexity.

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GLOBAL SENSITIVITY ANALYSIS IN THE LIMITED DATA SETTING WITH APPLICATION TO CHAR COMBUSTION

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ABSTRACT

In uncertainty quantification, variance-based global sensitivity analysis quantitatively determines the effect of each input random variable on the output by partitioning the total output variance into contributions from each input. However, computing conditional expectations can be prohibitively costly when working with expensive-to-evaluate models. Surrogate models can accelerate this, yet their accuracy depends on the quality and quantity of training data, which is expensive to generate (experimentally or computationally) for complex engineering systems. Thus, methods that work with limited data are desirable. We present a new diffeomorphic modulation under observable response preserving homotopy (D-MORPH) regression to train a polynomial dimensional decomposition surrogate of the output that minimizes the number of training data. The new method first computes a sparse Lasso solution and uses it to define the cost function. A subsequent D-MORPH regression minimizes the difference between the D-MORPH and Lasso solution. The resulting D-MORPH surrogate is more robust to input variations and more accurate with limited training data. We illustrate the accuracy and computational efficiency of the new surrogate for global sensitivity analysis using mathematical functions and an expensive-to-simulate model of char combustion. The new method is highly efficient, requiring only 15% of the training data compared to conventional regression.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL DEM-BASED COUPLED 3D THERMO-HYDROMECHANICAL MESOSCOPIC MODEL FOR MODELLING FLUID FLOW IN VERY-LOW POROSITY MATERIALS

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ABSTRACT

Most of the physical phenomena in engineering problems occur under non-isothermal conditions. Moreover, even if the physical system is initially in a state of thermodynamic equilibrium, the physical phenomena or chemical reactions that occur may lead to local temperature changes and consequently to heat transfer. Therefore, understanding heat transfer in particulate systems is of great importance to many engineering applications such as environmental science, chemical and food processing, powder metallurgy, energy management, geomechanics and geological engineering. The need to consider the effect of heat transfer becomes critical in analyses of many multi-field problems in porous and fractured materials. The heat transfer may occur e.g. by diffusion, advection and radiation. Complex coupled thermal-hydraulic-mechanical (THM) processes, including heat transfer, fluid flow and material deformation simultaneously occur and are affected by many non-linear processes.

A novel DEM-based pore-scale 3D thermo-hydro-mechanical model of two-phase fluid flow [1] combined with heat transfer in non-saturated porous materials of very low porosity for fracture propagation is presented. The model is based on a direct numerical simulation approach. Numerical calculations were carried out for bonded granular specimens with a 3D DEM fully coupled with 3D CFD (based on a fluid flow network) and 3D heat transfer that linked discrete mechanics with fluid mechanics and heat transfer at the meso-scale. The heat transfer was related to both the fluid (diffusion and advection) and bonded particles (conduction). The coupled thermal-hydraulic-mechanical (THM) model was validated by comparing the numerical results with the analytical solution of the classic 1D heat transfer problem. Bonded particle assemblies with two different grain distributions were considered. Perfect accordance was obtained between numerical and analytical outcomes. In addition, the effects of advection on the cooling of a bonded particle assembly were numerically shown. Finally, the authors' previously developed DEM-based 2D THM model [2] was compared with a novel 3D pore-scale THM model.

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Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE REVISITED PHASE-FIELD APPROACH TO BRITTLE FRACTURE: APPLICATION TO THE BRAZILIAN FRACTURE AND WING-CRACK PROBLEMS

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ABSTRACT

In a recent contribution, Kumar et al. (2020, 2022) have introduced a comprehensive macroscopic phase-field theory for the nucleation and propagation of fracture in linear elastic brittle materials under arbitrary quasistatic loading conditions. The theory can be viewed as a natural generalization of the phase-field approximation of the variational theory of brittle fracture of Francfort and Marigo (1998) to account for the material strength at large. This is accomplished by the addition of an external driving force—which physically represents the macroscopic manifestation of the presence of inherent microscopic defects in the material—in the equation governing the evolution of the phase field. Through comparisons with experiments in materials soft and hard under various loading conditions, it has been shown that this theory may be a complete theory of fracture for brittle materials.

This talk will focus on the application of the theory to two problems involving fracture under large compressive forces: (1) Brazilian fracture (diametral compression) test and (2) Wing-crack evolution test. Such problems have proved to be challenging for the classical phase-field models, and various energy splits have been proposed in the literature to accurately describe experimental observations. We will show that the theory of Kumar et al. can intrinsically capture the compression-tension asymmetry without requiring an energy split.

From an application point of view, this talk will discuss how to correctly interpret the results of the Brazilian fracture test to measure tensile strength. Our analysis shows that the formulas proposed by the latest ASTM standard for the Brazilian test generally do not yield correct values for the material's tensile strength. A new protocol is proposed to deduce the tensile strength of a material from a Brazilian test. Moreover, for the wing-crack evolution test, the analysis shows that wing cracks can be obtained even when the mode II fracture toughness is equal to the mode I fracture toughness, in contrast to previous claims in the literature that mode II fracture toughness has to be much higher.

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Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NONLINEAR MECHANICS OF REMODELING AND GROWTH

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ABSTRACT

We present a large-deformation formulation of the mechanics of evolving biological solids. Specifically, we focus on the phenomenon of remodeling and growth. Remodeling is anelasticity with an internal constraint—material evolutions that are mass and volume-preserving. On the other hand, growth involves material evolutions that are not mass-preserving. The explicit time dependence of the energy function is via an evolution tensor (remodeling or growth) that is (are) the internal variable(s) of the theory. The evolution tensor is defined from a multiplicative decomposition of the deformation gradient into an elastic and a evolution deformation gradient. The constitutive behavior is described through a two-potential approach which involves specifying energy storage and dissipation mechanisms through two scalar potentials. The novel component of our formulation is that we propose an additional energy storage mechanism, which we call an evolution energy (remodeling or growth energy). We argue that the competition between the evolution energy and strain energy drives the evolution process. The governing equations of evolving solids are derived using the Lagrange-d'Alembert principle.

We investigate two examples of material remodeling and growth. First, we investigate the remodeling of collagen fibers in soft tissues through an idealized study of finite extension and torsion of transversely isotropic solid circular cylinders. Second, we study the bulk growth of arteries, idealizing them as isotropic finite-length thick shells.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHASE FIELD FRACTURE APPROACH TO MODEL COMPLEX CRACK INTERACTIONS IN FIBER REINFORCED POLYMER COMPOSITES

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ABSTRACT

Damage and failure in fiber-reinforced polymer composites (FRPCs) often result from a complex interplay of factors, including matrix cracking, fiber breakage, fiber-matrix debonding and delamination. FRPCs are commonly used in applications where plies with different or same fiber orientations are stacked together to form a layered structure. Analyzing the interaction between the cracks originating and propagating in the bulk with the delamination along interfaces poses a significant challenge. To analyze this phenomenon, we have developed an anisotropic interface regularized phase field approach in a 2D configuration where damage initiates from bulk and interacts with the interface fracture and vice-versa. However, the 2D implementation is not enough to predict the twisting of the crack in the out-of-plane direction. Therefore, in this work we also attempt to characterize the crack propagation that happens along complex paths using a phase field model in a 3D fiber-reinforced composite laminate. In the proposed formulation, the phase field smears the sharp interfaces as regularized cohesive zones and describes the bulk crack surface density allowing interaction between bulk crack and interface damage. In this way, the displacement jump created by the sharp interface separation is approximated as a smooth transition based on a first-order Taylor series expansion of the assumed smoothed regularized displacement field.

We developed an approach to model the constitutive behavior of the FRP composite as a homogenized material consisting of an elastic matrix and axially deformable fibers characterized by the fiber volume fractions and orientations. By developing a 3D phase field model, we were able to predict the bulk fracture and delamination and their complex interactions for different layups such as 90-90, 90-45, 90-0, and other fiber directions that could not be well captured in 2D due to the out-of-plane deformation. Moreover, by analyzing the crack interaction in both 2D & 3D configurations under mode I, II, & III loading cases, we were able to provide deeper insights into the intrinsic failure mechanisms, including fiber/matrix debonding and kinking, matrix crack propagation, and delamination between the adjacent plies where more geometrical complexities are involved. The model was implemented in ABAQUS/Standard by writing a user-element subroutine (UEL) to understand the fracture behavior of composite laminates in various loading conditions.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FRAMEWORK FOR THE TOPOLOGY OPTIMIZATION OF MULTI-PHYSICS, MULTI-MATERIAL MICROSTRUCTURES USING NEURAL NETWORKS

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ABSTRACT

In structural applications, the optimal topology of single-material microstructures, i.e., architected materials, can be easily computed to maximize bulk modulus, minimize Poisson ratio, etc. However, in many real-world applications, it is important to also consider thermal quantities of interest; this necessarily entails the use of multiple materials, where one material exhibits superior structural properties, while the other exhibits superior thermal properties.

We consider here such multi-physics, multi-material, microstructural topology optimization problems, where the coefficient of thermal expansion (CTE) along with bulk modulus and Poisson ratio, serve as objective and constraints. To solve such problems, that are of significant interest in the aerospace industry, we propose a neural-network (NN) framework where the NN's weights and biases are used to capture the topological density field. The benefits of the NN framework over the classic mesh-based representation are that: (1) the NN representation is inherently independent of the underlying mesh, (2) the functional richness of the NN can be exploited to discover complex topologies, and (3) the gradients can be computed accurately and automatically using backward propagation.

The framework is illustrated using two types of problems: (1) where a structural property such as bulk, shear, or Poisson ratio serves as the objective, while a constraint is imposed on the CTE, and (2) where the CTE serves as the objective, while structural quantities serve as constraints. Several numerical examples are presented to illustrate the merits of the proposed framework.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATIONAL MODELLING OF COLD-FORMED STEEL BEAM FOR IMPROVED SEISMIC PERFORMANCE USING OPTIMIZATION

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[1]Indian Institute of Technology Kanpur

ABSTRACT

The utilization of cold-formed steel (CFS) beams in moment-resisting frames (MRFs) has recently gained significant attention among researchers. It offers advantages such as lighter weight, cost-effectiveness, and faster construction. However, the CFS section is slender, making the members susceptible to buckling. Nevertheless, due to the low bending stiffness of the CFS sheet, it can be bent into any desired cross-section. Consequently, this capability allows for optimizing CFS cross-sections to improve structural performance. This study aims to improve the seismic performance of CFS flexural members by developing a methodology to obtain improved structural performance with enhanced non-linear post-peak behaviour. A detailed finite element (FE) model was developed using ABAQUS, considering material and geometric non-linearity. This model was subsequently validated with results available in the literature. A multi-objective genetic algorithm is linked to FE analysis to optimize the CFS cross-section to maximize moment capacity and ductility. Four cross-section prototypes were optimized, and the results were compared based on the Pareto front. Furthermore, based on simulation results, limit states of failure that cause the degradation of the stiffness and strength of the beam are identified. Additionally, seismic performance criteria such as energy dissipation and the effect of cyclic loading have been investigated.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GEOMETRIC PHASE IN ELASTIC WAVES: EXPLORING DIFFERENTIAL GEOMETRY, TOPOLOGY, AND DESIGN APPLICATIONS

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ABSTRACT

The geometric phase, initially described as an additional phase factor in adiabatically varying quantum systems, has been found to be a relevant parameter across a wide array of dynamical systems with adiabatically varying parameters. Geometric phases influence light propagation in optical fibers, molecular energy spectra measured by vibrational spectroscopy, atmospheric radio waves, and elastic waves in structures. The persistence of this concept across different areas of wave physics and dynamics, as well as its ability to provide important mathematical insights to physical observables is due to its foundation on differential geometry and topology. The interplay between differential geometry, topology, and dynamics can also be leveraged to discover new ways to manipulate elastic waves in elastic topological metamaterials. Notably, these metamaterials exhibit backscattering immune wave propagation even in the presence of inhomogeneities and defects. Our presentation aims at reviewing the concept of geometric phase in the context of elastic waves, illustrating its connection with differential geometry and topology, and its role in the design of elastic topological waveguides.

The review and analysis proceed in three steps. First, a discussion of how both the topological and non-topological geometric phase arises in the context of elastic waves is presented. Flexural waves in helical waveguides are presented as an example of nontopological geometric phase. Then, an original contribution is presented to illustrate the emergence of the topological geometric phase in a one-dimensional waveguide with slowly varying cross section.

Second, the geometric phase is explained from a theoretical perspective by using concepts of differential geometry. Topology considerations are discussed in order to classify one-dimensional elastic waveguides into topological non-trivial systems.

Finally, the relevance and role of the geometric phase, and of differential geometry and topology are examined as they pertain to the design of elastic waveguides and their application to the classification of one-dimensional elastic metamaterials is presented.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING RIBBONS/STRIPS AS A COSSERAT ROD

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ABSTRACT

This study presents a computational approach to obtain nonlinearly elastic constitutive relations of strip/ribbon-like structures modeled as a special Cosserat rod. Starting with the description of strips as a general Cosserat plate, the strip is first subjected to a strain field which is uniform along its length. The Helical Cauchy-Born rule is used to impose this uniform strain field which deforms the strip into a six-parameter family of helical configurations-the six parameters here correspond to the six strain measures of rod theory. Two vector variables are introduced to model the position of the deformed centerline of the strip's cross-section and to model orientation of thickness lines along the strip's width. The minimization of the strip's plate energy together with the aforementioned uniformity in strain field reduces the partial differential equations of plate theory from the entire mid-plane of the strip to just a system of nonlinear ordinary differential equations along the strip's width line for the above mentioned two vector variables. A nonlinear finite element formulation is further presented to solve the above mentioned set of ordinary differential equations. This, in turn, yields the strip's stored energy per unit length as well as the induced internal force, moment and stiffnesses of the strip for every prescribed set of six strain measures of rod theory. The proposed scheme is used to study uniform bending, twisting and shearing of a strip. For the case of uniform twisting and shearing, the strip is also seen to buckle along its width into a more complex configuration which are accurately captured by the presented scheme. We demonstrate that the presented scheme is more general and accurate than the existing schemes available in the literature.

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Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDITIVE MANUFACTURING OF STIFF AND STRONG STRUCTURES BY LEVERAGING PRINTING-INDUCED STRENGTH ANISOTROPY IN TOPOLOGY OPTIMIZATION

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ABSTRACT

Anisotropy in additive manufacturing (AM), particularly in the material extrusion process, plays a crucial role in determining the actual structural performance, including the stiffness and strength of the printed parts. Unless accounted for, anisotropy can compromise the objective performance of topology-optimized structures and allow premature failures for stress-sensitive design domains. This study [1] harnesses process-induced anisotropy in material extrusion-based 3D printing to design and fabricate stiff, strong, and lightweight structures using a two-step framework. First, an AM-oriented anisotropic strength-based topology optimization formulation optimizes the structural geometry and infill orientations, while assuming both anisotropic (i.e., transversely isotropic) and isotropic infill types as candidate material phases. The dissimilar stiffness and strength interpolation schemes [2] in the formulation allow for the optimized allocation of anisotropic and isotropic material phases in the design domain while satisfying their respective Tsai–Wu and von Mises stress constraints. Second, a suitable fabrication methodology realizes anisotropic and isotropic material phases with appropriate infill density, controlled print path (i.e., infill directions), and strong interfaces of dissimilar material phases. Experimental investigations show up to 37% improved stiffness and 100% improved strength per mass for the optimized and fabricated structures. The anisotropic strength-based optimization improves load-carrying capacity by simultaneous infill alignment along the stress paths and topological adaptation in response to high stress concentration. The adopted interface fabrication methodology strengthens comparatively weaker anisotropic joints with minimal additional material usage and multi-axial infill patterns. Furthermore, numerically predicted failure locations agree with experimental observations. The demonstrated framework is general and can potentially be adopted for other additive manufacturing processes that exhibit anisotropy, such as fiber composites.

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METAMODELING FROM BAYESIAN PERSPECTIVE

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ABSTRACT

A novel Bayesian synergistic metamodeling (BSM) for model configuration towards a synergy between physical knowledge and data is introduced. A core issue for modeling is to fully utilize the available information to construct a reliable model that represents the input-output relationship of concern. Previous studies have highlighted the detrimental impacts of modeling discrepancies on subsequent analyses [1,2]. To address this issue, the proposed BSM fuses the understanding of the concerned physical mechanism and the implicit features extracted from the captured data to develop the most suitable representation of the underlying input-output relationship [3]. The model discrepancy of physical information infused metamodeling is compensated via data-driven metamodeling. The resultant synergistic model achieves the optimal balance between data fitting and model complexity. Moreover, by exploiting Bayesian inference, the uncertainties of all estimates are quantified to reflect the quality of the estimation and prediction. The proposed BSM overcomes critical issues in conventional modeling and provides a generic framework to leverage the explainability of physical principles and the flexibility of data-driven techniques for model development. To demonstrate the performance of the proposed BSM, a simulated example under various modeling conditions and a case study for seismic attenuation modeling with in-situ records will be discussed.

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Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIGH-ORDER IMPLICIT-EXPLICIT SCALAR AUXILIARY VARIABLE (SAV) TIME INTEGRATION SCHEMES FOR STRUCTURAL DYNAMICS

Sun-Beom Kwon[1] and Arun Prakash[1]*

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ABSTRACT

In recent years, the scalar auxiliary variable (SAV) approach [1] has emerged as a robust method for developing high-order time integration schemes with energy stability. Researchers have developed various time integrators based on the SAV approach. However, these SAV schemes are designed for solving first-order ordinary differential equations (ODEs). Thus, there is a compelling motivation to extend their applicability to problems governed by second-order ODEs such as structural dynamics.

We introduce novel high-order implicit-explicit scalar auxiliary variable (IMEX-SAV) time integration schemes which directly solve second-order ODEs without transforming the equations into a different form. The proposed schemes treat linear terms implicitly and nonlinear terms explicitly, thus avoiding the need for iterations. The underlying time integrator used is the kth-order backward difference formula (BDFk). We prove the energy stability of the proposed schemes in both linear and nonlinear structural dynamics. Furthermore, a local truncation error analysis for both homogeneous and forced response is carried out to investigate the convergence rates of the proposed kth-order IMEX SAV schemes ($1 \leq k \leq 5$). The theoretical convergence rates are validated through convergence tests.

We present several numerical examples of linear and nonlinear structural dynamics to evaluate the performance of the proposed schemes. These include a two-dimensional (2D) Howe truss, a simple pendulum, a spring-pendulum combination, and a multi-degree-of-freedom (MDOF) Duffing oscillator. In summary, the key features of the proposed IMEX SAV schemes include (1) no need for iterations for nonlinear terms; (2) unconditional energy stability; and (3) higher-order accuracy.

Reference:

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SYSTEM-RELIABILITY-BASED DISASTER RESILIENCE ANALYSIS FOR POWER GRIDS CONSIDERING CAUSALITY EFFECTS OF CASCADING LINE OUTAGES

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ABSTRACT

In light of rapid social development, civil infrastructure systems have undergone a remarkable increase in complexity, rendering them vulnerable to external and internal hazards. The escalating climate disaster also urges system managers and policymakers to swiftly implement measures to mitigate the socioeconomic losses resulting from these risks. Against this backdrop, the concept of disaster resilience, which refers to the comprehensive ability of a system and surrounding society to cope with and manage various risks, has gained great attention. This study applies a novel disaster resilience analysis framework to a regional-scale power grid from a system reliability perspective to address the pressing research needs. The framework begins by discerning the occurrence rates of hazards and spatially distributed characteristics of hazard intensity on line components. The reliability (β)-redundancy (π) analysis identifies probable outage scenarios induced by hazards and computes component-level reliability indices (β) and the final system-level redundancy indices (π) for each identified scenario. In particular, the analysis considers subsequent outages of line components using cascading simulation models, given the flow-based nature of power grids. Each cascading stage delineates the state of the line by its inner demand flow to power capacity and redistributes surplus power from outages to other remaining lines as moving on to the next simulation stage. The causal effects of individual lines in influencing grid state are quantified by the β-π analysis results and the causal diagram describing the systems under hazards. The quantified causal effects are incorporated into the system resilience evaluation to avoid spurious correlations arising from common source effects on component failures. Numerical investigations underscore the framework's practicality in assessing the seismic resilience of power grids. The investigations demonstrate that the pattern of cascading line outages varies depending on the power capacity conditions and emphasize the need to set appropriate levels of line capacity margins and system-level performance goals to ensure the resilient operation of the network. It is also revealed that, under certain conditions, unconditional protection or restoration of specific lines may be detrimental to the disaster resilience of the entire system. In conclusion, the proposed approach is expected to improve decision-making strategies for the disaster resilience of power grids and facilitate a priori scenario-based analysis.

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPLORING DIMENSIONALITY REDUCTION IN SURROGATE MODELS FOR STORM SURGE TIME-SERIES PREDICTIONS

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ABSTRACT

Surrogate models or metamodels have proven to be an attractive alternative for storm surge estimation over large areas of interest. After calibration on a pre-existing high fidelity synthetic storm database, they are able to provide efficient and accurate approximations of the expected storm surge, emulating the results that an expensive high fidelity hydrodynamic numerical simulator would offer. Recent work of the author focused on providing time series surge predictions simultaneously for thousands of locations of interest using a Gaussian Process metamodel. One of the investigated alternatives involved addressing the spatio-temporal variability through the metamodel output, relying on the fact that predictions typically are established for the same locations and time instances. This allows for the treatment of each time-step and location as a separate output leaving the storm features as the only component determining the surrogate model input. In an effort to improve computational efficiency for both metamodel calibration and implementation stages, a linear dimensionality reduction technique was applied in the output, that allowed the calibration of independent metamodels in the latent space. This presented work here, seeks to investigate whether alternative non-linear dimensionality reduction techniques, such as autoencoders, facilitate a faster, yet accurate metamodel development in the latent space, similar to the established approach. Comparison will be drawn for the North Atlantic Coast Comprehensive Study time-series database having over 12,000 locations of interest and around 120 time steps across the 595 landfalling storm scenarios.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MOLECULAR SIMULATION OF CEMENT PHASES' RESPONSE TO HIGH TEMPERATURES

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ABSTRACT

Our goal is to enhance our comprehension of the fundamental mechanisms governing thermally induced damage in cement-based materials (CBM) through molecular modeling and simulations. This investigation serves as the foundation for constructing a multiscale model of CBM, integrating insights from the nanoscale physics of structural characteristics and water dynamics. Microstructural analysis highlights the crucial role of dehydration in the thermal decohesion of cement paste. Quantifying the dehydration process during heating involves assessing microstructural changes and water mass loss within the porous structure of Calcium-Silicate-Hydrate (C-S-H). The precipitation of C-S-H largely governs the pore size distribution and connectivity of the cement porous network. At the molecular scale (less than 1nm), interlayer water and interfacial adsorbed water at grain surfaces of C-S-H emerge as pivotal contributors to the dehydration process at high temperatures. This water's pore-size-specific dynamics pose a challenge to existing continuum-based models typically applied at larger scales than those of C-S-H grains and nanopores. To capture the multiscale hierarchical nature of the C-S-H gel and its porosity network, a combined approach employing both molecular and continuum modeling is imperative. Molecular simulations will provide crucial inputs for the mesoscale model, offering insights unattainable through conventional experimental techniques and ultimately informing macroscopic constitutive relationships.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF DISCRETE AND CONTINUOUS SOIL CONTACT IN THE TOPOLOGY OPTIMIZATION OF LARGE-SCALE STRUCTURES

Romulo Cortez[1], Iago Cavalcante[2], Emanuel Tavares[2], Raghavendra Sivapuram[3], Persio Leister de Almeida Barros[2], Renato Picelli[1] and Josue Labaki[2]*

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ABSTRACT

The behavior of large-scale structures is strongly affected by their interaction with their foundation and supporting soil. This vouches for the importance of taking this effect into account when designing these structures. This paper explores the effect of foundation and soil flexibility in the design of structures via topology optimization. We consider the case of discrete contact, in which the structure is supported by pile groups, which are then responsible for transferring the borne load to their surrounding soil, as well as the case of continuous contact, in which the structure is in direct contact with the soil surface. The discrete contact case is modeled using classical finite elements to model the structure, together with the impedance matrix method to model the pile group. Direct continuity and equilibrium conditions at the interface between the structure and the pile group are establish to describe the coupling. Topology optimization is obtained using the Bi-directional Evolutionary Structural Optimization (BESO) method under various boundary conditions, with the goal of minimizing the compliance of the piled structure under a prescribed volume restriction. The continuous contact case is modeled via a coupling of the Indirect Boundary Element Method (IBEM) to model soil response and the Finite Element Method (FEM) to model the supported structure. Topology optimization is obtained using the Topology Optimization of Binary Structures (TOBS) method, to minimize structural compliance under volume constraints. Both analyses consider the case of a tall tower under vertical and horizontal loads, and the case of bridges under external loads. The results from both studies show that soil and foundation flexibility strongly affect the achievable optimization goal and cause the optimization algorithm to find significantly different optimal topologies, when compared to a first approximation considering rigid support for the structures.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL ANALYSIS OF BANDGAP-INDUCING PROPERTIES OF 1D AND 2D SANDWICH FOUNDATIONS

Luis Filipe do Vale Lima[1], Leonardo Antoniazzi Marques[1], Euclides Mesquita[1] and Josue Labaki[1]*

[1]University of Campinas

ABSTRACT

In engineering practice, vibration attenuation devices such as tuned mass dampers and isolators play a crucial role in enhancing structural resilience and minimizing the potential damages induced by dynamic forces. One example is base isolation devices, which improve the seismic response of structures and make them more resilient to earthquake-related structural damage. This paper investigates the vibration attenuation performance of periodic foundations for structures. A numerical method is proposed, which considers the structure to be a one- or two-dimensional linear-elastic body under external and seismic loads. The soil in this problem is modeled as a homogeneous half-space under dynamic point loads in the 1D case, or via the Indirect Boundary Element Method (IBEM) in the 2D case. Coupling between the response of the soil and of the structure is obtained via direct continuity and equilibrium conditions at the interface. Loading is imposed in terms of time-harmonic external loads or seismic excitation. The model is used to study three different configurations of foundations that are placed at the soil—structure interface: 1) no foundation 2) homogeneous foundation 3) sandwiched foundation. The third case comprises a foundation that is built by layering two different materials in an alternate fashion. The material properties and thickness of the layers are selected to induce prescribed bandgaps in the response of the structure. The performance of the three systems is compared in terms of their ability to attenuate vibration of the structure due to external and seismic excitation, but also in terms of their ability to attenuate vibration that is propagated through the soil from the structure. The results are presented in terms of data that can be directly applied in engineering practice.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VALIDATION OF LHPOST6 SHAKE TABLE-SPECIMEN MODEL USING SHAKE TABLE TEST DATA

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ABSTRACT

The NHERI□UC San Diego Large High-Performance Outdoor Shake Table (LHPOST) was commissioned on October 1, 2004. The LHPOST was recently upgraded from its previous 1-DOF to its current 6-DOF configuration with funding from the National Science Foundation and additional funding resources provided by the University of California at UC San Diego. The LHPOST was closed for operations in October 2019 to enable the construction of the upgrade and reopened for operations in April 2022, under its new name, the LHPOST6.

A numerical dynamic model of the LHPOST6 under bare table condition was developed to represent the open-loop dynamics of the shake table system, namely from the servovalve command signals to the achieved platen motion. The model was validated in both open-loop and closed-loop simulation using experimental data acquired during the acceptance and characterization tests performed on the LHPOST6 in the period July 2021 – April 2022. The LHPOST6 model is also programmed to have the flexibility to interact with structural analysis software via TCP/IP protocol by transferring (i) the platen acceleration along each of its 6-DOFs from the shake table model to the specimen model (developed in the structural analysis software) and (ii) the total base reaction forces and moments of the specimen model to the shake table model.

The dynamic model of the LHPOST6 developed in Matlab-Simulink coupled with the dynamic model of a specimen developed in the structural analysis software (e.g., OpenSees) is used to simulate the dynamic response (or achieved response) of the LHPOST6 and the dynamic response of the specimen tested on the table. The LHPOST6-specimen model is validated by recent shake table tests performed on the full-scale 10-story, cross-laminated timber (CLT) TallWood building specimen. It is also used to investigate the control-table-specimen interaction during these landmark tests. Results from the validation study and the investigation of the table-specimen interaction will be presented.

The validated numerical dynamic model of the LHPOST6 loaded with a test specimen can be used for: (1) pre-test simulation of shake table tests (i.e., planning and designing shake table experiments), (2) off-line tuning or pre-tuning of the shake table controller accounting for the test specimen dynamic characteristics, (3) safe off-line training of shake table operators, and (4) investigating table-specimen interaction (i.e., interpreting the results of shake table experiments). It will also be instrumental for developing: (1) hybrid shake table testing methods, and (2) the next generation of shake table controllers.

Recent advances in mechanical energy harvesting and its applications in structural health monitoring and control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING AND EVALUATING PERFORMANCE OF PIEZOELECTRIC-MULTIPLE TUNED MASS DAMPERS FOR VIBRATION REDUCTION AND ENERGY HARVESTING

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[1]National Central University

ABSTRACT

In this study, the equation of motion for the proposed cantilever beam type Piezoelectric-Tuned Mass Damper (Piezo-TMD) is derived. By converting the equations of motion into state-space representation, the system can be analyzed in a more comprehensive manner. By eigenanalysis of the state-space system matrix, the piezoelectric damping ratio can be obtained from the eigenvalues. The piezoelectric damping ratio represents the capacity of mechanical vibration energy dissipation in the Piezo-TMD, which energy dissipation is practically converted into electricity by the direct piezoelectric effect. Therefore, the piezoelectric damping ratio serves as an indicator of its energy harvesting efficiency. The system identification of a manufactured prototype Piezo-TMD confirms the consistency of numerical model with real vibration responses. Moreover, when the largest piezoelectric damping ratio is achieved, the Piezo-TMD is resulting in both maximum vibration reduction and power generation. In order to enhance the vibration reduction and energy harvesting performance of the Piezo-TMD, a group of Piezo-TMDs is assembled into Piezoelectric-Multiple Tuned Mass Dampers (Piezo-MTMDs). In the Piezo-MTMDs, each Piezo-TMD is individually optimized for mass and resistance, so that not only dispersing their frequencies around the natural frequency of the primary structure but also with electrical and mechanical simultaneously tuning. Numerical simulations of the Piezo-MTMDs installed in an aeroelastic model are conducted to evaluate the performance of vibration reduction and energy harvesting effects. Results from the frequency response function and time history analysis demonstrate that the Piezo-MTMDs effectively reduce the vibration of the primary structure and exhibit efficient energy harvesting capabilities.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCEMENTS IN ENERGY-CONSERVING CONTACT THEORY: BRIDGING THE GAP AND ENHANCING COMPUTATIONAL PERFORMANCE

Zhengshou Lai[1]*

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ABSTRACT

The energy conserving contact theory, initially introduced by Yuntian Feng (2021, CMAME), has exhibited notable success across various applications. However, two significant challenges have hindered its widespread implementation. The first challenge involves establishing connections with conventional contact models, while the second pertains to addressing discretization convergence issues. To address these challenges, this study introduces two formulations of contact potential: an analogy of the linear contact model and an analogy of the Hertzian contact model. Additionally, we establish a comprehensive relationship between the parameters of the proposed contact theory and those of conventional contact models. The energy conservation characteristic is rigorously verified through a two-particle colliding and bouncing test, where we thoroughly investigate and address the critical timestep issue. To further validate the proposed framework, discrete element simulations are conducted for a triaxial compression test and a column collapse test, involving both spherical particles for verification purposes and general star-shaped particles. The results showcase the accuracy, efficiency, and numerical stability of the developed approach. This work not only advances the understanding of energy-conserving contact theory but also provides a robust and versatile framework that bridges the gap with conventional models, offering enhanced computational performance across diverse applications.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEURAL OPERATORS FOR PARAMETRIC STRUCTURAL RESPONSE PREDICTION AND SYSTEM IDENTIFICATION

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[1]*The Hong Kong University of Science and Technology*

ABSTRACT

Neural operators have been recently proposed for learning mappings between function spaces, compared with conventional neural networks, they show more powerful generalization performance. Here, we introduce the parameter-time-(space) decomposition “inductive bias” to the current neural operator framework. We design a decomposed neural operator, applying it to investigate both the forward problem (structural response estimation) and inverse problem (system identification) in structural health monitoring (SHM). Specifically, in structural response estimation, the decomposed neural operator learns the mapping from the system’s parameter space, and excitation space to the response space; in system identification, the decomposed neural operator learns the mapping from the excitation space and response space to the the system’s parameter space. Subsequently, we consider a numerical Duffing oscillator system and an experimental structure system for validating the proposed model. Comparisons between the decomposed neural operator, vanilla neural operator, and conventional neural network are conducted, and the results show that the decomposed neural operator shows better generalization performance in both forward and inverse problems for SHM.

A CONSTITUTIVE MODEL FOR CRUSHABLE GRANULAR MATERIALS WITH NON-SPHERICAL PARTICLES

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[1]Northwestern University

ABSTRACT

This study explores the profound influence of the particle shape on the mechanical properties of crushable granular materials, particularly in the realms of mineral processing and geomechanics. Despite widespread recognition of the significance of particle morphology in these fields, prevailing continuum theories for engineering applications frequently overlook the evolution of the grain shape during comminution processes.

Addressing this gap, our study introduces an innovative constitutive modeling approach tailored for crushable granular continua with non-spherical particles and evolving shape characteristics. Leveraging the foundational principles of Continuum Breakage Mechanics (CBM), a theory originally designed to monitor changes in particle size distributions during confined comminution, we propose the inclusion of multiple grain shape descriptors. These descriptors are treated as essential variables influencing the elastic strain energy potential and are integrated as dissipative state variables within the model. Motivated by observations of extreme fragmentation in nature, our model postulates the gradual convergence of these additional shape descriptors toward an attractor. To validate the proposed constitutive law, we conduct comprehensive comparisons with various benchmarks, including laboratory experiments and Level Set discrete element analyses. The results demonstrate the promising performance and accuracy of the theory in capturing the intricate mechanics of crushable granular materials.

This constitutive model not only expands the scope of existing theories but also provides valuable insights into the complex interplay between particle shape, compressive yielding, and inelastic deformation in granular continua. Given the prevalence of granular materials in both natural and engineered environments, understanding their mechanical behavior at the microscale is paramount for predicting and mitigating structural failures. The proposed model contributes significantly by emphasizing the often-overlooked role of the particle shape in the overall behavior of crushable granular materials, thus paving the way for improved predictive capabilities and more robust engineering solutions

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL SIMULATION OF HARDENED 3D-PRINTED ULTRA HIGH PERFORMANCE CONCRETE USING THE LATTICE DISCRETE PARTICLE MODEL

Erol Lale[1], Ke Yu[1], Matthew Troemner[2] and Gianluca Cusatis[1]*

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ABSTRACT

The Lattice Discrete Particle Model (LDPM) is adept at simulating the fracture behavior of concrete, particularly at the scale where major material heterogeneities, such as coarse aggregate sizes, are prevalent. This model creates a meso-structure representation of concrete by employing a stochastic method to generate spherical particles. This generation process is informed by several key parameters: the cement content, the water-to-cement ratio, and the range of aggregate sizes, encompassing both the maximum and minimum sizes. The lattice framework of the model is established through Delaunay tetrahedralization, specifically targeting the centers of the aggregates. This approach leads to the formation of polyhedral cells around each aggregate fragment, achieved through a three-dimensional domain tessellation process. LDPM is integrated into Project Chrono, an open-source multi-physics simulation engine. This implementation leverages the C++ programming environment and adheres to object-oriented programming principles. It is utilized for the numerical analysis of 3D printed ultra-high performance concrete samples. To accurately represent the geometry of these samples, a 3D scanner is employed to capture their exact dimensions. These scanned geometries are then imported into the FreeCAD preprocessor for meso-structure creation. In this framework, various mechanical tests are simulated, including unconfined compression and three-point bending tests. The model allows for the application of different load orientations relative to the casting direction of the samples. The results from these simulations are compared with experimental data to validate the model's accuracy and effectiveness in replicating real-world behavior of ultra-high performance concrete under various loading conditions.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN MODEL UPDATING OF TING KAU BRIDGE AND ITS VERIFICATION BY MEASURED INFLUENCE LINE

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ABSTRACT

This presentation focuses on the practical finite element model (FEM) updating of a long-span cable-stayed bridge in Hong Kong – Ting Kau Bridge following the Bayesian statistical system identification framework utilizing measured modal parameters. The FEM was developed in ABAOUS, and a PYTHON-ABAQUS interface was developed for implementing Bayesian model updating algorithm in PYTHON and link it to the FEM in ABAQUS. The posterior probability density function (PDF) of uncertain model parameters was approximated by samples from Markov chain Monte Carlo (MCMC) simulation. As a result, it is not necessary to assume the type of posterior PDF before model updating. The model updating results are sensitive to the selection of model classes. Furthermore, the cross-sectional area of the main girder of the bridge deck is a key parameter influencing the lower modes of the bridge. To verify the updated FEM, a full-scale vehicular load test was conducted on the bridge to obtain the displacement influence line through GPS sensors. The results demonstrate that the characteristics of the FEM updated using the proposed Bayesian model updating framework based on measured dynamic properties are consistent with the structural characteristics of the physical bridge.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISION-BASED TRAFFIC LOAD IDENTIFICATION FOR VISUAL WEIGH-IN-MOTION

Phat Tai Lam[1] and Hyungchul Yoon[1]*

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ABSTRACT

With the rapid development of the transportation industry, identifying moving loads plays a significant role in maintaining and operating the transportation infrastructure system. Existing load identification methods typically rely on collecting vehicle load data from weigh-in-motion systems (WIM) when vehicles pass over them; however, cumbersome installation, high-cost, and regular maintenance are the main obstacles that prevent WIM from being used in practice. Therefore, developing a feasible and effective approach capable of simultaneously monitoring the position and loads of vehicles is crucial. In recent years, computer vision techniques have gained widespread adoption in reliable and accurate applications due to their advantages of being low-cost, non-contact, and simple to deploy. This paper proposes a non-contact moving load identification method that leverages the advancement of computer vision technology. First, a vehicle detector based on the YOLOv8 framework is applied to detect and track the vehicle's position through the traffic camera. While another camera is installed at a specific area on the roadside to capture the vehicle tire's images, the instance segmentation and optical character recognition techniques can be used to extract the tire deformation parameter and tire inflation pressure from tire images. Then, the vehicle's weight is established by applying the physical principle that the force between tires and the road is equivalent to the product of contact pressure and contact area. Finally, the moving loads are identified by matching the time when the vehicle moves into the camera area with the time when the vehicle's tire image is captured. To verify the potential of this method, field experiments were conducted with empty and full passenger cars. This low-cost, non-contact proposed method has demonstrated the feasibility of computer vision techniques to overcome the limitations of existing moving load identification approaches.

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PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GLOBAL SENSITIVITY ANALYSIS OF SOUND TRANSMISSION IN DOUBLE-WALL STRUCTURES WITH A POROUS LAYER USING KRIGING METAMODEL

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ABSTRACT

This research focuses on the sensitivity analysis of sound transmission loss in a double-wall structure with a porous layer exposed to a diffuse field using the Kriging metamodel. The system is modeled in the low-frequency range using the finite element method [1], and the transmitted acoustic power is calculated using the Rayleigh integral method. Biot theory is employed to model the porous material, considering an elastic matrix. The Biot model is ideal when dealing with porous materials interacting with elastic structures, as it effectively handles their interaction, unlike simpler models such as the equivalent fluid model. The local equations for the coupled studied elastic-acoustic-poroelastic problem involve the elastic structure displacement, the solid phase displacement of the porous material, the fluid phase pressure within the porous material, and the acoustic cavity pressure.

The study aims to investigate the impact of geometric and material parameters of the system on its acoustic transmission loss coefficient. In this context, global sensitivity analysis is used to identify influential and less influential parameters in the proposed model. To do that, Sobol indices, a global method based on output variance analysis (ANOVA) developed by Sobol [2], are applied. These indices quantify the contribution of each parameter, aiding in the identification of critical inputs and revealing complex parameter relationships and interactions. Calculating sensitivity indices through Sobol indices with Monte Carlo simulations can be computationally demanding, especially for finite element models with many parameters. To overcome this limitation, the Kriging metamodel [3], also known as Gaussian process modeling, is used to approximate the output of our model at a lower cost.

The results of this study indicate that the most influential parameters for improving the acoustic performance of the system within the specified frequency range are, in order of importance, the thickness of the plates, the thickness of the acoustic cavity, and the resistivity of the porous material.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELUCIDATING THE EFFECT OF MATERIAL UNCERTAINTY ON SEISMIC FRAGILITY OF REINFORCED CONCRETE FRAMES

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ABSTRACT

The uncertainty in material properties of reinforced concrete frames governs the uncertainty in their seismic behavior. In this work, we investigate four, eight, and twelve-storey reinforced concrete frames by considering the uncertainty in properties of concrete and steel. Latin hypercube sampling technique is used to obtain 200 sets of variations of the material properties. Hence, a total of 600 buildings are analyzed through nonlinear dynamic analyses using a suite of 184 near-field ground motion by considering average spectral acceleration as the intensity measure. Further, we study the effect of material uncertainty and record-to-record variability on total variability. Machine learning models are then used, which take input of material properties, fundamental period, and the number of stories of the building and predict the fragility curve parameters (median and standard deviation) corresponding to three limit states, i.e., Immediate Occupancy, Life Safety, and Collapse. Explainability is an integral part of the machine learning pipeline. Therefore, SHAP analysis is used to explain the model predictions, which revealed that the fundamental period of the building and the material properties of concrete govern the fragility curve parameters. It is also observed that with an increase in the severity of the limit state from the Immediate Occupancy to the Collapse limit state, the contribution of steel rebars increases towards the standard deviation parameter of the fragility curve. We also make a graphical user interface to predict the fragility curve parameters.

FATIGUE LIFE ESTIMATION OF CVOW OFFSHORE WIND TURBINES USING STRAIN MEASUREMENTS

Sophia Lauterbach[1], Bridget Moynihan[1], John DeFrancisci[1], Eleonora Maria Tronci[1], Babak Moaveni[1] and Eric Hines[1]*

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ABSTRACT

Offshore Wind Turbines (OWT) experience a significant number of cycles with different levels of strains on the tower during their operation or idling conditions. This paper investigates which factors contribute most to the overall fatigue of the structures by conducting fatigue analysis on Coastal Virginia Offshore Wind (CVOW) monopile Turbine A01. The tower is instrumented with strain gauges and accelerometers, and data is collected continuously since September 2023. We collected and analyzed measured vertical strains at two tower levels, and then used the strain readings to calculate the bending moments at two directions and two levels. With these moments and available SCADA data, we evaluated how operational conditions such as yaw angle, power, and wind speed, affect the moments experienced at the upper and lower levels. The next phase of analysis evaluated the fatigue of the turbines, which was done at sixteen stations around the circumference of the lower level of the turbine. Cumulative damage per station is computed using the Miner’s rule and the remaining useful life of the turbine is estimated using appropriate S-N curves.

AI-ENABLED XNODE: INTEGRATION OF ARTIFICIAL INTELLIGENCE CAPABILITIES INTO WIRELESS SMART SENSOR PLATFORMS FOR RAILROAD BRIDGE IMPACT DETECTION

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ABSTRACT

Low-clearance railroad bridges are susceptible to impacts from over-height vehicles; therefore, researchers have developed approaches to identify the occurrence of these impacts on railroad bridges. The most common approach involves the use of sensors for impact detection. However, there remains the challenge of determining the nature of impact and deciding whether the impact is critical or not . While some previous works have previously been done on data processing from sensors utilized in structural health monitoring (SHM) of civil infrastructure, most approaches make use of cloud computing. The challenge is that for time-sensitive applications like impact detection, cloud computing results in extra processing time. In this study, we develop an artificial intelligence-based framework for edge implementation on wireless smart sensors for SHM. A traditional wireless smart sensor platform, XNode, is employed to design an AI-enabled Xnode for making machine learning predictions at the edge. This framework is demonstrated using impact detection on-edge, and the result shows the potential of implementing edge computing for such time-sensitive structural health monitoring applications.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIZE EFFECT ON STRENGTH STATISTICS OF NOTCHED QUASIBRITTLE STRUCTURES

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ABSTRACT

This talk presents a stochastic analysis of the size effect on the nominal strength of quasibrittle structures with a large pre-existing notch. This type of scaling behavior has been extensively studied within a deterministic framework. Very little attention is paid to stochastic analysis. Stochastic FE simulations are performed to study the failure of geometrically similar beams of different sizes. The numerical analysis uses a~continuum damage model, in which the tensile strength and fracture energy are modeled by homogeneous random fields. Different correlation lengths are considered as a parametric study. The analysis yields the size effects on both the mean and coefficient of variation (CoV) of the nominal structural strength. It is shown that the size effect on the mean strength agrees well with the Bazant size effect model. The simulation predicts a strong size effect on the CoV of the nominal strength. The small, intermediate, and large-size asymptotes are derived analytically for the scaling behavior of the strength CoV. Based on these asymptotes, an approximate scaling equation is proposed for the CoV of nominal strength. The effect of correlation length on the simulated failure behavior is discussed.

Advancements in wind engineering: From atmospheric boundary-layer processes to resilient built environments
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE EFFECTIVENESS OF MODELING POROUS ELEMENTS IN OPENFOAM TO LIMIT POLLUTANT RE-ENTRAINMENT AND PEDESTRIAN WIND DISCOMFORT

Viet Le[1], Shinya Kondo[1], Rubina Ramponi[1] and Pia Riedel[1]*

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ABSTRACT

Adverse wind conditions in the built environment can cause discomfort and harm to users within occupied spaces. Strong wind flows can limit activities, reduce “feel temperatures”, and carry pollutants to the public realm. Conversely, weak wind flows can create stagnant air in poorly ventilated area, leading to excessive thermal heat or health risks.

These undesirable conditions reduce the value of a development and limit the utility of a programmed space; therefore, designers, planners, engineers, and stakeholders look to wind studies to understand flow conditions within their site. In some cities such as San Francisco, Boston, and Toronto, these wind studies are required as part of planning submissions for new developments. Wind tunnel testing is typically used to perform these assessments and can provide the wind speed at specific points of interest and visualizations of expected flow conditions. Another approach that many have turned to in recent years is employing numerical methods using computational fluid dynamics (CFD). With a computational model of the development, a wind assessment can efficiently be performed for large areas of interest and include additional considerations such as ambient temperature conditions or pollutant exhausting equipment.

Both wind tunnel testing and CFD studies identify undesirable areas caused by excessive windiness or lack thereof. Projects in early design stages can alleviate these unwanted conditions through alterations to the massing or building orientation. If issues arise during later stages, a common approach to alleviate them is through small-scale mitigation measures. These include porous canopies or screens that divert or reduce wind flows around the site. Including porous elements in CFD studies increases model complexity and computational costs. To work around these issues, a common solution is to model these mitigation measures implicitly through ‘porous zones’ that act as momentum and turbulence sources/sinks in the region domain. The difficulty of this technique, however, is the limited guidance in literature for modelers in selecting the appropriate loss coefficients for different types of architectural screens.

This presentation discusses two case studies where both explicit and implicit modelling were adopted to represent a series of louvers in a CFD model and to evaluate their impact in limiting pollutant re-entrainment and pedestrian wind discomfort. Detailed, explicit modeling of the louver elements was carried out to compare flow behavior and inform the large-scale implicit model. The case studies outline the viability and limitations of using implicit modeling techniques to represent small-scale mitigations in commercial CFD studies.

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT ASSESSMENT OF NETWORK SEISMIC FRAGILITY CURVES USING SUBSET SIMULATION

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ABSTRACT

Various empirical and analytical methods have been developed to evaluate the seismic fragility curves of individual structures for efficient risk assessment of lifeline networks against earthquakes. However, the analysis of seismic network reliability, such as connectivity reliability (e.g., two-terminal and k-terminal connectivity) and capacity reliability (e.g., k-out-of-N:G and k-out-of-N:F reliability), is more critical for community-level safety and resilience. Therefore, beyond fragility curves of structures, this study proposes a variance-reduction sampling framework to assess fragility curves in terms of network connectivity and network capacity using subset simulation. Network reliability analysis often faces inherent challenges, such as complex network topologies, interdependencies among seismic uncertainties, and low-probability network failures. While various simulation-based approaches such as the crude Monte Carlo simulation are highly flexible and scalable, they are highly inefficient for low-probability network failure events. To overcome this limitation, we reformulate the binary limit-state function used for network connectivity analysis into piecewise continuous limit-state functions. The reformulations enable the application of subset simulation by measuring the path length or vulnerability between target origin and destination nodes. Each function shows different performance in terms of computational speed and accuracy. Both proposed limit-state functions quantify how close each sample is to the network failure, thereby facilitating the construction of intermediate relaxed failure events. Constructing a connection between the intermediate failure events and seismic intensity, a single implementation of Hamiltonian Monte Carlo-based subset simulation can generate the seismic fragility curve of a lifeline network. Furthermore, the combination of this framework with order statistics can extend its application to capacity reliability analysis, which has been considered computationally challenging for analytical approaches. Numerical examples demonstrate that the proposed framework can accurately and efficiently evaluate network fragility curves.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIDE-ANGLE VIDEO-BASED CABLE DISPLACEMENT MEASUREMENT FOR CABLE-STAYED BRIDGES

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ABSTRACT

Due to the deterioration of cable-stayed bridges, the importance of maintaining existing structures has been emphasized. For the maintenance of structures, several studies are using the Vibration-based Structural Health Monitoring method to evaluate the current condition of the structures. To use Vibration-based Structural Health Monitoring, it requires the dynamic response of the structure, such as displacement, acceleration, or strain. Recent advancements in computer vision techniques have improved the conventional vibration measurement method into a more convenient and efficient approach. As a result, vision-based displacement measurement methods have been used for measuring displacement in infrastructure structures such as cable-stayed bridges. However, traditional vision-based displacement measurement methods require the assumption that the movement of the cable displacement should be measured in parallel to the camera plane. Hence, for some cases, it is not easy to decide the appropriate location for the camera installation. Therefore, this study proposes a new method to measure cable displacement of cable-stayed bridges measurement using side-angle video. The new method comprises three sequential steps. Firstly, it involves estimating the camera intrinsic matrix and extrinsic matrix, calculated through the camera calibration. Secondly, it includes tracking the target in the cable using the KLT (Kanade-Lucas-Tomasi) tracker to determine the target's 2D image coordinate location. Lastly, it determines the cable displacement in the 3D world coordinates by combining the camera pose obtained in step 1 with the 2D image coordinate location of the target in step 2. The proposed method is anticipated to alleviate limitations in determining appropriate camera locations when employing vision-based displacement measurement methods.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PREDICTION OF MICROBIAL-INDUCED CALCIUM CARBONATE PRECIPITATION AND ITS APPLICATION IN SELF-HEALING CEMENTITIOUS MATERIAL

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ABSTRACT

Microbial-induced calcium carbonate precipitation is a biochemical (i.e., biomineralization) process that utilizes microbial metabolic activities to facilitate the precipitation of calcium carbonate (CaCO3) in the existence of nutrients and calcium sources. Various applications of MICP, such as soil stabilization, permeability control, bioremediation of toxic heavy metals or contaminants, sealing leakage paths, carbon sequestration, etc., have been widely studied in past years. The exploration of self-healing cementitious material has recently shown that MICP is one of the most promising healing methodologies. In this study, we investigate the chemical and enzyme kinetics of the MICP pathway with a focus on ureolytic bacteria. The ureolytic bacteria (i.e., urease-production bacteria) is a heterogeneous microorganism with the urease enzyme. The indigenous urease enzyme produced inside the microorganism catalyzes the urea hydrolysis (ureolysis) reaction to form ammonia and carbonic acid. The carbonic acid shifts to bicarbonate ions through the bicarbonate equilibrium and then reacts with calcium ions to precipitate calcium carbonate. The calcium sources in cementitious material are usually abundant, such as calcium hydroxide and acetate. A mathematical model is proposed in this study to predict the quantity of calcium carbonate precipitation with given initial conditions and chemical kinetic constants. The proposed model considers the bacterial growth and attachment, the temperature and pH effect on the urease catalytic rate, the dissociation of ammonia, the pH variation of the solution, the shift of bicarbonate equilibrium, and the precipitation of calcium carbonate. The output of the model gives (1) the variation of the concentration of chemicals and biomass involved in the MICP, (2) the volume ratio of precipitated calcium carbonate, and (3) the distribution of various chemicals and biomass if considering fluid transport. Several benchmark simulations are demonstrated to show the model results. Experimental studies are performed to calibrate the model. Finally, the predicted CaCO3 precipitation volume ratio from the model output is defined as a healing ratio hd. The hd value is a crucial parameter in the damage-healing computational scheme, which is used to compute the material’s fracture-healing response. The proposed model can be applied to various MICP healing problems of the cementitious material that utilizes ureolytic bacteria. Based on the prediction of the proposed MICP model, we can estimate the mechanical strength recovery of a healed cementitious material.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING THE UNCOUPLED DAMAGE-HEALING BEHAVIOR OF SELF-HEALING CEMENTITIOUS MATERIAL WITH PHASE FIELD METHOD

Hsiao Wei Lee[1], Li Meng[1], Amirreza Sadighi[1], Alireza Ashkpour[1], Mohammad Irfan Iqbal[1], Geetika Mishra[1], Christopher Sales[1], Yaghoob Amir Farnam[1] and Ahmad Najafi[1]*

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ABSTRACT

The self-healing cementitious material implemented with internal vascular networks to transport healing agents has recently received attention. However, the ideal healing agents (or strategies) were still in discussion. In this study, we utilize microbially induced calcium carbonate precipitation (MICP) as the healing strategy. MICP is a biochemical process that utilizes microbial metabolic activities to precipitate calcium carbonate ($CaCO_3$) in the existence of nutrients and calcium sources, which can be used for damage-healing by crack filling. We developed a computational uncoupled damage-healing framework to predict the fracture-healing responses of a multifunctional vascular cementitious composite. The framework integrates a numerical self-healing model based on MICP chemical kinetics into a damage model developed using the phase-field method. This uncoupled damage-healing framework includes three stages. In stage 1, the fracture and crack propagation in a virgin concrete sample with an embedded vascular network is simulated using the conventional phase-field method. The damage variables at the material points of each element are computed. In stage 2, the concrete sample is unloaded. We assume the bacteria and necessary chemicals are transported through the vascular network and are immediately available to react at the crack sites. The quantity of $CaCO_3$ precipitation through MICP reaction is simulated using the numerical self-healing model. The healing ratio, hd, defined as the crack's filling ratio by precipitated calcite, will be correlated with the computed $CaCO_3$ precipitation quantity through experimental observations. The damaged part is assumed to be completely healed when hd=1 and not healed at all when hd=0. Therefore, we can update the damage variables at the material points of each element to the phase-field damage model based on the healing ratio, i.e., hd value. Finally, in stage 3, the fracture and crack propagation of the healed concrete sample is then simulated again using the phase-field method. We observe that the simulated load-displacement curve of the healed cementitious material shows a recovery in stiffness depending on the MICP healing ratio, which can be easily calibrated with experimental data. The proposed framework can be applied to various fracture-healing problems of vascular cementitious materials that adopt MICP as the healing strategy.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SCAN-TO-FEM: DIGITAL TRANSFORMATION OF TRUSS BRIDGE

Jaehyuk Lee[1] and Hyungchul Yoon[1]*

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ABSTRACT

The digital twin is a technology that represents real structures in a digital model. However, the digital twinning process for structures like bridges is complex. This complexity arises because it involves collecting data reflecting the aging of actual structures and implementing them into finite element models. Conventional methods rely on manual measurements and design drawings, incurring significant costs and time delays. To address these issues, our research proposes utilizing drones and AI for the digital twinning of truss bridges. The proposed technology consists of two main phases: Semantic Structure from Motion (SSfM) as the first phase and Scan-to-FEM as the second phase.

In the first phase, we obtain a 3D point cloud reflecting semantic information about bridge components. Drones are used to scan the bridge, and based on the scanned photo data, Structure from Motion (SfM) and Semantic segmentation techniques are applied to generate a 3D point cloud. The second phase involves creating a finite element model of the truss bridge from the 3D point cloud. Recognizing joints as nodes and bars as elements, we generate the finite element model. This model can serve as an initial value for model updating. The proposed technology is expected to reduce costs and time associated with the bridge's digital twinning process.

A GENERALIZED MODEL FOR PREDICTING POWER OUTAGES IN TEXAS DURING EXTREME WEATHER EVENTS: INTEGRATING LAGGED INFORMATION, GEOGRAPHICAL, CLIMATIC, AND SOCIO-DEMOGRAPHIC DATA

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ABSTRACT

In February 2021, an unprecedented winter storm, “Uri,” landed in the southern United States, inflicting severe damage, particularly in Texas. According to Buchele (2023), infrastructure such as power plants, transmission lines, and gas distribution systems in southern states like Texas are predominantly designed to endure summer heat rather than winter cold. Consequently, these regions suffer significant damage due to their vulnerability to winter storm Uri. The economic damages from this event in Texas are estimated to exceed $195 billion (The City of Austin and Travis County, 2021), underscoring the critical need for a robust predictive model for power outages. Precise forecasting can enable the strategic distribution of electricity to the most vulnerable areas, effectively reducing the scale of power disruptions.

Lee and Paal (2023) emphasized the significance of population density as a key predictor in power outage projections, which correlates with imbalances in electricity supply and demand. Their study further demonstrated that utilizing data from just two hours prior can yield a predictive accuracy with a coefficient of determination of over 0.8. However, the models proposed by Lee and Paal (2023) are primarily tailored for specific scenarios such as winter storm Uri, limiting their applicability to other extreme weather events.

Therefore, the primary objective of this current study is to develop a more generalized model capable of predicting power outages under other extreme weather conditions (e.g., other winter storms, floods, and hurricanes). This research involves analyzing outage data spanning from 2014 to 2022. The development of this model is expected to substantially reduce the adverse impacts of power outages across a spectrum of extreme weather conditions. Accurately predicting such events will enhance the effectiveness of preparedness and response strategies, contributing significantly to the resilience and stability of power infrastructures in vulnerable regions.

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Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CLASSIFICATION OF BRIDGE MEMBERS USING PCD TRAINING AND PARAMETRIC BIM ALGORITHMS

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ABSTRACT

Recent studies have focused on creating Building Information Modeling (BIM) models incorporating various structures, materials, and properties using spatial information from 3D point cloud data (PCD). The efficient and automatic scanning to BIM process necessitates the development of PCD classification into members and then the generation of BIM library for these members. The classification of members from PCD is time-consuming, prompting a deep learning based process that can automatically classify members. However, a large amount of PCD training data poses challenges, particularly for civil structures, which require outdoor and multiple scans under various surrounding conditions Thus, there are limitations in acquiring a large amount of PCD for the training of deep learning algorithm. In this study, an algorithm is proposed to generate extensive PCD training data from BIM models. The proposed approach involves a parametric semi-automatic BIM generation process using Dynamo. In other words, BIM bridge models are generated using library that contains shape information for each member. For this, parameters are defined accounting for different types of superstructures, piers, and abutments. These parameters specify the shape information of each member and adapt to various dimensions of the member shape. The parametrically generated bridge BIM model is then converted into PCD using a proposed conversion algorithm, which serves as PCD training data for the automatic member classification within the deep learning algorithm. The proposed parametric BIM generation and PCD conversion algorithms were applied to a real bridge to evaluate the accuracy of the learned member classification. PCD of real bridges contain unnecessary objects. Thus, this study further developed a preprocessing algorithm semi-automatically to remove these unwanted objects and obtain noise-free bridge PCD. The proposed deep learning algorithm showed high accuracy in member classifications in the PCD of real bridges.

OPTIMAL SENSOR PLACEMENT IN AMBIENT VIBRATION TEST USING VALUE-OF-INFORMATION ANALYSIS

Binbin Li[1]*

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ABSTRACT

Ambient vibration test (AVT) is becoming a practical means for assessing the performance of civil structures. Optimizing the implementation of AVT is attractive not only for reducing costs but also for improving the accuracy and precision of the identification process. The recent development of ‘uncertainty laws’ for AVT, i.e., analytical formulae that express identification uncertainty in terms of test configuration, provides a scientifically sound basis for this purpose. Based on the assumption of long data and small damping, the uncertainty laws allow one to assess or even optimize a number of factors in AVT, e.g., the length of the record and the type of sensors. However, they do not resolve all the problems, e.g., the number of sensors to use and the locations to place them. In this paper, we combine the uncertainty laws, which provide the pre-posterior distribution of modal parameters, and value-of-information analysis, which gives the principle to achieve an optimal test configuration for AVT. Modeling the mode shape as a Gaussian random field, the objective of sensor optimization is to minimize the uncertainty in the identification of all modal parameters (frequencies, damping ratios and full mode shapes). In order to avoid the arbitrary assignment of utility (or cost) value to the identification uncertainty, we formulate the problem as a budget-constrained optimization. A practical solution strategy is developed. A fully-instrumented lab model is used to validate the proposed method. An optimal AVT planning for a high-rise building is provided to illustrate its application to a real-world project.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING WITH KNOWLEDGE TRANSFER FOR RAPID ESTIMATION OF SMALL FAILURE PROBABILITY OF LARGE-SCALE NONLINEAR DYNAMIC SYSTEM

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ABSTRACT

Evaluation of rare event probability of large-scale nonlinear dynamic systems subject to natural hazards is of great interest in applications such as the safety and performance assessment of buildings. An important challenge in determining these probabilities is the inherently high computational demand brought about by the sizable number of nonlinear dynamic analyses necessary at the heart of most general-purpose stochastic simulation schemes during uncertainty propagation. To address this issue, this research leverages machine learning with knowledge transfer in developing a general uncertainty propagation framework for rapid evaluation of small failure probabilities of high-dimensional nonlinear systems subjected to stochastic excitation. The proposed method incorporates a non-intrusive LSTM-based nonlinear response simulator into an advanced stratified sampling scheme using transfer learning. This not only reduces the required sample size for estimating small failure probabilities but also significantly reduces the computational demand associated with dynamic analysis, thereby enhancing efficiency. In particular, the high-dimensional mapping between excitation and responses is spatially and temporally reduced to a low-dimensional mapping between the projected inputs and projected responses through basis functions obtained from proper orthogonal decomposition and wavelet approximation. Subsequently, the low-dimensional mapping is learned directly by a long short-term memory (LSTM) network. The LSTM-based response simulator is first calibrated through data generated based on the distribution of the largest hazard intensity measures occurring in the most extreme stratum. Subsequently, rapid transfer learning is performed to adapt the calibrated LSTM-based response simulator to other strata of the sampling space with diminished training effort, establishing a set of response simulators covering the entire sampling space of the hazard. The framework is illustrated through case studies focused on large-scale nonlinear and dynamic structural systems subjected to wind or earthquake excitation. The framework is proven to be highly efficient and remarkably accurate in estimating small failure probabilities associated with multiple limit states of interest.

DERIVATIVE-FREE APPROACH FOR BOTH TIME AND FREQUENCY DOMAIN FINITE ELEMENT MODEL UPDATING

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ABSTRACT

Finite Element (FE) models are crucial for predicting structural behavior under diverse loading conditions in structural engineering. This research develops a derivative-free methodology for finite element model updating in both time and frequency domains. The proposed approach conceptualizes these problems as stochastic dynamic systems, incorporating parameter-to-data mappings to facilitate the estimation of unknown model parameters. The unscented Kalman filter is utilized as a robust tool for solving these dynamic systems, enabling efficient parameter updating. Sparsity regularization is further investigated, aiming to induce sparsity in the estimated parameters. This feature is particularly beneficial in applications like damage identification, where it leads to more precise and interpretable outcomes. The efficacy and robustness of the proposed derivative-free approach are demonstrated through comprehensive simulations, showcasing its potential in accurately determining unknown parameters in FE models for various structural engineering applications.

COMPLEX NONLINEAR SYSTEM RESPONSE MODELING AND PARAMETER IDENTIFICATION VIA A REAL-TIME UPDATING PHYSICS-INFORMED NEURAL NETWORK

Huaguan Li[1] and Chao Sun[1]*

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ABSTRACT

Bolted joint loosening is a major threat to the structural safety of oil and gas pipeline systems and steel structures. Accurate structural response prediction can advance the understanding of the complex dynamic behaviors and enable effective structural health monitoring (SHM). Due to bolt loosening damage, a pipeline system exhibits nonlinear and time-varying characteristics under external excitations, which makes the structural response highly complex and challenging to be accurately predicted by traditional methods. To address this issue, this study proposes a real-time updating physics-informed neural network (PINN) to predict structural response of a pipeline system with joint loosening damage. A Runge-Kutta cell modeling ordinary differential equation (ODE) of structural dynamics is integrated with the recurrent neural network (RKRNN) to implement machine learning to predict the pipeline system responses. To better capture the nonlinear and time-varying characteristics caused by joint loosening, a real-time updating strategy is proposed to update the modal parameters (natural frequencies and damping ratios) at each time step to reduce the discrepancy between predicted result and testing data. Performance of the proposed method is examined via a laboratory case study of a pipeline structure with two bolted flange joints. Research results show that the proposed real-time PINN method can accurately predict the pipeline structural responses under different joint loosening damage conditions. The proposed method has the potential to address modeling uncertainty/errors and is applicable for joint loosening identification of complex pipeline systems and steel structures with bolt connections.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AUTOMATING SYNTHETIC DATA GENERATION FOR DEEP LEARNING-BASED DAMAGE DETECTION IN CONCRETE DAMS

Abhishek Doodgaon[1], Jian Li[1], Caroline Bennett[1] and Remy Lequesne[1]*

[1]University of Kansas

ABSTRACT

Regular inspections are crucial for identifying and assessing a wide range of damage states in concrete dams. Manual inspections of dams are often constrained by cost, time, safety, and inaccessibility. Leveraging automation capabilities by using image data and artificial intelligence can enhance the efficiency and accuracy of dam inspection. Deep learning models have proven highly effective in detecting a variety of damage features using images. Supervised learning, a machine-learning approach that tackles classification problems by using labeled examples in which each training data point includes features (damage images) and a corresponding label (pixel annotation), relies on availability of high-quality and diverse training data. Unfortunately, public datasets of damage images from concrete dams are scarce and inconsistent in quality, quantity, and representation, and human annotation can be costly in terms of time investment.

To address this challenge, we present a novel approach that involves synthesizing a realistic environment using a photorealistic 3D model of a dam. By overlaying this model with synthetically created concrete damage textures with controllable lighting conditions, we can render images to generate reliable datasets. Our pipeline uses NX CAD/Blender for 3D model generation, Substance 3D Designer for texture synthesis and automation, and Unreal Engine 5 for creating a realistic environment and rendering images. This approach enables generation of an abundance of high-quality datasets along with the ground truth, which are essential for training accurate deep learning models. In addition, the automation capabilities of the software enable flexible and scalable generation of datasets, overcoming the constraints of time.

CLIMATE ADAPTIVE DESIGN FOR COMMUNITY RESILIENCE ASSESSMENT: A TEMPORAL RETROFIT METHODOLOGY FOR A CHANGING CLIMATE

Jiate Li[1] and John van de Lindt[1]*

[1]Colorado State University

ABSTRACT

Hurricanes can be devastating events and are anticipated to increase in intensity due to climate change, posing risk to life, property, and social institutions and economies. The potential intensification of hurricanes in the US introduces additional uncertainties to hazard simulation models in the long term. It is important for communities to implement effective adaptation strategies to attain long-term resilience goals and ensure sustained development when facing a changing climate. In this study a temporal retrofit methodology aims to provide decision support for community stakeholders in adapting to future hazards and achieving resilience goals. The methodology comprises three dimensions: future hazard levels, community impact, and climate adaptation levels. Hurricane projections under various climate scenarios describe future hazard levels. These projections take into account uncertainties introduced by climate change. The cumulative impact on a community is quantified by socioeconomic factors (e.g., the number of residents leaving the community periodically over a century due to hurricanes). This methodology simplifies decision-making for community stakeholders by offering straightforward information about the extent of community impact under different climate scenarios based on a chosen level of adaptation strategy. An illustrative example has been developed for the virtual community Centerville, focusing solely on residential buildings. However, the entire methodology can be extended to include various community components, such as infrastructure, schools, hospitals, and commercial buildings which is underway by the authors.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PRACTICE OF MACHINE LEARNING IN EVALUATING THE PROPERTIES AND MECHANICAL BEHAVIORS OF SOILS

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ABSTRACT

Although many prediction methods for soil properties and constitutive models have been proposed, most of them are derived from limited experimental results and applied to specific soils and testing conditions. Therefore, unified prediction models that can be applied to predict the soil properties or mechanical responses are still unavailable.

In this study, we focus on two representative examples: evaluation of thermal conductivity and modeling of mechanical behaviors in frozen soils using machine learning methods. To predict the thermal conductivity of soils, we compiled a large database consisting of 2197 data points from various literature sources. Six machine learning algorithms, namely multivariate linear regression (MLR), Gaussian process regression (GPR), support vector machine (SVM), decision tree (DT), random forest (RF), and adaptive boosting methods (AdaBoost), were employed to predict the thermal conductivity based on this database. The results indicate that AdaBoost yields the most accurate predictions, with minimal errors (RMSE = 0.099), outperforming the other five models and three conventional models.

To model the mechanical behaviors, we propose a novel data-driven approach based on Long Short-Term Memory (LSTM) for frozen soil. A compiled database of stress-strain data from triaxial tests on frozen silty sandy soil is used to train the LSTM model. The model captures the mechanical responses under various temperatures and confining pressures. Besides, we investigate and incorporate uncertainty in stress-strain relations (deviatoric stress and volumetric strain to axial strain) using LSTM-based modeling with Monte Carlo dropout (LSTM-MCD). The results demonstrate that the LSTM model accurately predicts the stress-strain responses of frozen soil without uncertainty. Furthermore, the LSTM-MCD model with uncertainty analysis provides 95% confidence intervals for evaluating the mechanical responses of frozen soil.

This study highlights the advantages of data-driven models with uncertainty in predicting soil properties and mechanical behaviors. It offers valuable insights for project construction and serves as a reference for related research endeavors.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REFINING AGGREGATE SIZE GRADATION IN COMMERCIAL CONCRETE FOR IMPROVING DURABILITY AND SUSTAINABILITY

Linfei Li[1], Erfan Najaf[1], Maedeh Orouji[1] and Eric Landis[1]*

[1]University of Maine

ABSTRACT

Shrinkage stands out as a critical challenge impacting concrete durability, often manifesting in the earliest stages of its formation during hydration. This issue leads to the premature development of cracks, a concern notably observed within the initial seven days of casting-in-place concrete in Maine. The complexities of concrete shrinkage arise from diverse sources—high water-to-cement (w/c) ratios contribute to drying shrinkage, while low w/c ratios induce autogenous shrinkage. The prevalent use of cement as the primary binder also raises environmental apprehensions due to its significant role, occupying nearly 8% of total CO2 emissions. Addressing these challenges demands a strategic reduction in the cement content within the concrete matrix, presenting an opportunity to simultaneously enhance durability and sustainability. This study centers on optimizing aggregate size gradation to redefine the concrete matrix structure and diminish the reliance on binders. Comprehensive evaluations of mechanical performance and durability were conducted on the developed concrete. The findings substantiate a noteworthy achievement: the recommended mix reduces cement content by approximately 23%, surpassing the strength and durability metrics of commercially available concrete in Maine. This optimization showcases a promising avenue for minimizing environmental impact while fortifying concrete against shrinkage-related vulnerabilities.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRAPH NEURAL BAYESIAN OPTIMIZATION FOR SEISMIC RETROFIT PRIORITIZATION OF TRANSPORTATION NETWORKS

Min Li[1]*

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ABSTRACT

Bridge retrofitting can act as an effective pre-disaster mitigation measure to increase the transportation networks' resilience against future seismic events. However, bridge retrofit planning is costly and typically subject to limited resources. Thus, an optimal subset of bridges within the network is usually prioritized for retrofitting through optimization. Nevertheless, the optimization process often presents significant computational challenges. These challenges arise mainly from the high computational costs in evaluating the objective function, characterized by probabilistic metrics such as risk. Usually, Monte Carlo simulations are used to estimate these metrics, necessitating repeated evaluation of high-granularity simulation models used to quantify network performance. In addition, the optimization requires an enormous number of strategy combinations to be examined, especially for large transportation networks, which significantly increases the computational effort to identify the optimal strategy. To address the difficulties, this study proposes a Graph Neural Bayesian Optimization (GNBO) algorithm for efficient optimal retrofit selection of large transportation networks to minimize seismic risk. The seismic risk is selected as the annual expected loss of the network-level performance, quantified by travel time increases and trips lost due to network disruptions. Given its power in analyzing graph-structured data, a Graph Neural Network (GNN) is trained as a surrogate model of the original network model to accelerate the evaluation of network performance, leading to rapid and accurate estimation of the seismic risk. Instead of directly replacing the original network model for optimization, a Bayesian Optimization (BO) framework guided by the GNN is developed to adaptively improve the accuracy of the surrogate model and identify the optimal strategy. To demonstrate the efficiency and effectiveness of the proposed approach, it is applied to a transportation network in the Southern California region for prioritizing bridge seismic retrofit.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL INVESTIGATION OF TURBULENCE EFFECT ON FLIGHT TRAJECTORY OF SPHERICAL WINDBORNE DEBRIS: A MULTI-LAYERED APPROACH

Shaopeng Li[1], Kimia Yousefi Anarak[2], Ryan Catarelli[1], Yanlin Guo[2], Kurtis Gurley[1] and John van de Lindt[2]*

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[2]Colorado State University

ABSTRACT

Accurate modeling of the turbulent wind field is a crucial component of risk analysis for structures to windborne debris damage. Existing studies typically simplify the complexities of wind turbulence, and the potential influence on the accuracy of debris flight modeling has not been systematically demonstrated. This study takes a multi-layered approach to numerically simulate the flight trajectory of spherical debris in a turbulent wind field. Complexities are incrementally added to the simulated wind field to systematically investigate the influence of spatial correlation and non-Gaussian features of turbulence on debris flight behavior. The sensitivity of debris flight behavior to turbulent wind features will inform the design of debris flight tracking wind tunnel tests and building façade debris vulnerability modeling efforts.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ARBITRARY CURVATURE PROGRAMMING OF THERMO-ACTIVE LIQUID CRYSTAL ELASTOMER VIA TOPOLOGY OPTIMIZATION

Weichen Li[1] and Xiaojia Shelly Zhang[1]*

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ABSTRACT

Plants can change their morphology upon environmental variations such as temperature. Inspired by plants’ morphological adaptability, we present a computational inverse design framework for systematically creating optimized thermo-active liquid crystal elastomers (LCEs) that spontaneously morph into arbitrary programmed geometries upon temperature changes. The proposed framework is based on multiphysics topology optimization and a statistical mechanics-based LCE model to realize arbitrary curvature programming for LCE composites under large deformations. We propose a curvature-based optimization formulation that enables rotation-invariant and size-insensitive programmability of LCE, accounting for its highly nonlinear deformed shape. We demonstrate that the programmed LCE composites can accurately morph into a wide range of complex target shapes and curvatures, such as those of numbers, letters, flowers, and various objects. The resulting optimized designs exhibit highly irregular material distributions, which surpass intuition-based designs, and precisely produce desired deformed geometries upon temperature increase. The computational inverse design technique holds promise for a wide array of applications requiring function- and performance-driven design of active materials.

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FLOOD RESILIENCE IN POLE-MOUNTED SUBSTATIONS: STRUCTURAL FRAGILITY ASSESSMENT

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ABSTRACT

Electric Power Networks (EPNs) should ensure a resilient electricity supply even during extreme events. This study focuses on evaluating the resilience of substations, a key component of EPNs responsible for regulating, transforming, and distributing electricity, and often vulnerable to flood hazards.

Pole-mounted substations are the type that can effectively mitigate inundation failures by elevating electrical equipment. However, the supporting structures of such substations are often not designed to withstand flood flows and thus are prone to structural failure. In this study, a generalized framework is proposed to quantify the structural failure probabilities of pole-mounted substations and to assess their structural resilience to flooding. This framework is then applied to a case-study location in Malaysia, where serious flood events are common and pole-mounted substations are numerous.

The proposed framework can effectively address data limitations through well-justified assumptions. The study first identifies and quantifies the flood effects on the poles including pure hydrodynamic forces, the impact of floating debris, debris damming effects and scouring. The quantified flood effects are then compared with the structural capacity of a typical pole-mounted substation structure and its foundation, to derive a capacity threshold curve for structural failure. The failure probability is illustrated via fragility curves for different flood depths and risk curves for different flood and wind return periods, to further assess the substation's structural resilience. The aforementioned curves are based on a stochastic distribution of flood depths and velocities represented by a normalized Weibull function. A modifiable scale factor λ in this function (determined by the mode of flood depth or velocity) can be used to accommodate different geographical locations, which addresses the inherent uncertainties in assessing the resilience of structural systems to floods.

The research findings revealed that impact and damming effects arising from floating debris contribute the most (e.g., 40%–80%) to structural failure, which verifies that pole-mounted substations need to be designed to withstand flood effects in addition to wind loading. Besides, according to the developed risk curves, a flood return period of 25 years is recommended for designing substations to balance the structural capacity and costs. Overall, this study enhances the understanding of how component resilience relates to system-level risk in EPNs, and helps stakeholders, including those designing and managing substation structures, to quantify, assess and further enhance the flood resilience of EPNs.

PRIOR MODEL UPDATING WITH UNCERTAINTY QUANTIFICATION THROUGH VARIATIONAL BAYESIAN INFERENCE

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ABSTRACT

Earthquakes usually trigger ground failures like landslides and liquefaction, in addition to ground shaking, and further jointly result in significant building damage and loss of life. Therefore, rapid and accurate estimation of these hazards and their impacts is crucial for effective disaster response. However, the complex interactions among the various geophysical processes and co-located multiple hazards make accurate assessment of building damage and ground failures a challenging task. Our method addresses this challenge by using a variational Bayesian inference framework. This framework is designed to estimate building damage and various ground failures concurrently, by integrating data from building footprints, prior models, and Damage Proxy Maps (DPMs). This integrated approach allows for a more comprehensive assessment of seismic events. In variational Bayesian inference, prior models provide expert knowledge, act as constraints, and facilitate the Bayesian updating process. Incorporating new data, we update the priors and simultaneously derive posterior distributions. This process blends initial model assumptions with fresh insights from recent data, ensuring that our priors evolve, and our posteriors remain current, offering an accurate assessment of seismic risks. However, prior models frequently encounter limitations due to their reliance on oversimplified assumptions like linear approximations, a lack of specificity for localized conditions as they are often based on general datasets, and inherent uncertainties and generalizations from their broad application scope, which may lead to oversimplifications in handling individual seismic events.

In this work, we address the limitations of prior models by refining them with posterior distributions. Our focus is on distinguishing and quantifying two types of uncertainties: those inherent in the prior models and those emerging from remote sensing data. This crucial differentiation guides our iterative refinement process. We methodically diminish uncertainties intrinsic to the prior models while considering the fidelity of remote sensing data, enabling precise calibration of our updates. This process not only enhances the accuracy of our earthquake damage assessment models but also identifies areas needing additional data or refined modeling techniques. By integrating localized data and observations, our models become more precise, tailored to the unique characteristics of each earthquake-affected area. The resulting refined models provide a more accurate foundation for estimating future seismic event impacts, enriched with real-world data, and improved through uncertainty quantification. This approach marks a significant advancement in earthquake damage assessment, merging real-world data with advanced statistics for a more efficient understanding of earthquake risks, and leading to more accurate disaster response and planning.

MODELING PHASE-TRANSFORMATION INDUCED STRAIN LOCALIZATION USING A NEURAL-NETWORK ENHANCED REPRODUCING KERNEL PARTICLE METHOD

Xuejun Li[1] and Sheng-Wei Chi[1]*

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ABSTRACT

Reproducing Kernel Particle Method (RKPM) has demonstrated its proficiency in solving problems with extreme strain rates and severe material distortion, especially with the semi-Lagrangian (SL) formulation [1]. However, introducing the discontinuity in the approximation that captures heterogeneity, fracture, or strain localization remains challenging and lacks computational efficiency. Meanwhile, the application of Machine Learning (ML) has gained much attention in computational mechanics, e.g., solving elasticity problems with Physical-Informed Neural Network (PINN). Nevertheless, solving the equation solely by Neural Network (NN) without the aid of the existing numerical method may suffer from low efficiency and convergence issues. Therefore, incorporating NN to enhance the current numerical method, such as RK, has been proposed. A designated NN has been integrated into the RK approximation to enrich the discontinuity locally [2]. On the other hand, specific weights and biases can be derived to represent the analytical forms of the shape function in some well-known numerical methods, such as the Finite Element Method (FEM) [3]. Optimized relocation of the nodal points can also be accomplished to best produce the localized behavior within the minimum computation cost. In this research, a Neural Network (NN) based algorithm that utilizes specifically designed NN blocks to reproduce desired shape functions for the approximation is proposed and developed to better capture the localized behavior in the vicinity of the discontinuity in elasticity problems. Some additional improvements, such as the adaptive nodal refinement, can be made to augment the local behavior of discontinuity further. A set of benchmarks, including fracture process and strain localization due to phase transformation, is utilized to evaluate the proposed method's effectiveness in handling discontinuity in the solution of elasticity.

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Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECONFIGURABLE HIERARCHICAL ORIGAMI-BASED METASTRUCTURES

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ABSTRACT

Shape-morphing capabilities are crucial for enabling multifunctionality in both biological and artificial systems. Various strategies for shape morphing have been proposed for applications in metamaterials and robotics. However, few of these approaches have achieved the ability to seamlessly transform into a multitude of volumetric shapes post-fabrication using a relatively simple actuation and control mechanism. Taking inspiration from thick origami and hierarchies in nature, we present a new hierarchical construction method based on polyhedrons to create an extensive library of compact origami metastructures. A single hierarchical origami structure can autonomously adapt to over 1000 versatile architectural configurations, achieved with the utilization of fewer than 3 actuation degrees of freedom and employing simple transition kinematics. We uncover the fundamental principles governing theses shape transformation through theoretical models. Furthermore, we demonstrate the wide-ranging potential applications of these transformable hierarchical structures. These include their uses as untethered and autonomous robotic transformers capable of various gait-shifting and multidirectional locomotion, as well as rapidly self-deployable and self-reconfigurable architecture, exemplifying its scalability up to the meter scale.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LIFE-CYCLE RISK ANALYSIS AND DECISION-MAKING UNDER CLIMATE CHANGE

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ABSTRACT

In recent decades, the climate change impact has significantly influenced the occurrence and intensity of natural hazards such as typhoons and flooding globally and locally. The intensification of climate-related hazards presents an increasing challenge to the resilience of civil infrastructure systems. With the climate change impact contributing to non-stationary hazard occurrence, the traditional life-cycle risk assessment approach, which often relies on stationary Poisson models, is becoming inadequate. Furthermore, the conventional use of the expected economic loss as a common decision criterion is not able to capture the full spectrum of risks, particularly the worst-case scenarios of risks. Thus, this study proposes nonstationary stochastic processes such as non-homogeneous Poisson and mixed Poisson processes to consider the impact of climate change on hazard occurrence. The higher-order moments of economic loss and its quantile (also known as the Value at Risk) are proposed as additional risk measures for the life-cycle risk assessment. In addition to the risk quantification, it can be more challenging to identify the effects of climate change on decision-making. Climate change is associated with deep uncertainty, which defines the situation with a lack of or no information about the probabilities of possible outcomes. Addressing how to treat the deep uncertainties of climate change, which affect not only the stochastic frequency and intensity of hazards within the life-cycle analysis but also the subsequent decision-making process, is a critical issue. To address this, this study proposes an integrated life-cycle risk-informed decision-making framework that accommodates deep uncertainty by statistically accounting for its impact on hazard modeling and decision optimality. The adverse effects of choosing inappropriate decision alternatives are also assessed. The proposed framework is applied to a flood risk management problem subjected to extreme precipitation for illustration. The results show how deep uncertainty of climate change can be treated and statistically affects the decision optimality during the life-cycle analysis framework. This study aims to provide an evidence-based decision support framework on the risk mitigation and adaptation of civil infrastructure systems within a life-cycle context.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MONITORING OF LONG-TERM PRESTRESS LOSSES IN PREFABRICATED PRESTRESSED SLABS WITH COMPLEX CROSS SECTIONS USING LONG-GAUGE SENSORS

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ABSTRACT

Off-site fabrication allows for efficient production and construction, while prestressing process enhances the load-bearing capacity of structural components. Due to these advantages, the application of prestressed prefabricated structures increased significantly. The prestressing force is a crucial parameter to ensure the bearing capacity and durability of the prefabricated components. Throughout the service life of the structures, the magnitudes of prestressing forces, which are often reflected in the strain field in concrete, are expected to decrease due to redistribution of loads, creep and shrinkage, and material relaxation, etc. Therefore, it is of interest to monitor the long-term performance of prefabricated structural components by studying the internal strain distribution.

This paper aims at developing a methodology for monitoring long-term prestress losses in prefabricated prestressed beam-like concrete structures with a complex geometric cross-section. The methodology is validated on a double-T slab of a five-floor garage at Princeton University. Embedded long-gauge fiber Bragg grating (FBG) sensors are used for this purpose to monitor the strain in different directions. The main challenges of this research include: 1) verifying stability in temperature and strain sensors by identifying and calibrating malfunctions and drifts, 2) analyzing temperature variations between measurements, which requires accurate thermal compensation, 3) accounting for concrete material property changes compared to the initial prestressing phase, and 4) addressing the effects of creep and shrinkage on structural behavior.

The results show that the embedded long-gauge FBG sensors effectively capture the strain distribution during the first 2.5 years following construction, enabling the monitoring of long-term prestress losses. The findings of this study have important implications for the design, construction, and maintenance of prefabricated structural components, enabling enhanced safety and durability throughout their service life.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYSIS OF PLANE STRESS ELASTOPLASTICITY BY THE QUADRATURE ELEMENT METHOD

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ABSTRACT

Plane stress elastoplastic analysis is performed by the quadrature element method (QEM). Unlike the popular finite element method, the QEM first evaluates the integration in the weak-form statement of the problem by an integral quadrature scheme, and then approximates the differentiation at the discrete integration points by the differential quadrature analog. This approach avoids the explicit construction of shape functions and obtains higher-order elements simply by increasing the order of integration and differentiation. The usage of higher-order elements leads to more accurate solutions and coarser geometric meshes without detriment to the computational scale because the number of degrees of freedom is maintained. In addition, the element nodes in the QEM are the same as the integration points that possess physical meanings such as strains and stresses, which is crucial in the elastoplastic analysis for determining the elastic/plastic state of the nodes. A straightforward elastoplastic quadrature element formulation is developed. Incremental-iterative and return mapping solution schemes are adopted to implement the quadrature element for the elastoplastic analysis. Numerical examples are presented to demonstrate the effectiveness and high accuracy of the proposed approach.

Phase change materials (PCMs)-based multifunctional architected construction composites
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATION OF THE POZZOLANIC REACTION OF PHASE CHANGE MATERIAL (PCM)-LOADED DIATOMITE

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ABSTRACT

Diatomite, also known as diatomaceous earth (DE), is a biogenic siliceous sedimentary rock. Diatomite with pozzolanic activity has been studied as a cement additive or blend. However, diatomite has a highly porous structure, increasing water demand in concrete and limiting the use of diatomite as a mineral additive in the cement industry. With this weakness of diatomite in mind, a novel usage of diatomite as the carrier of PCM in the phase change concrete for thermal energy storage was proposed in the study. For diatomite, its pozzolanic reactivity is beneficial while its porous structure is adverse to the mechanical properties of cementitious materials; however, the porous structure of diatomite is an advantage as the absorber/carrier of PCM in the functional cementitious materials. Therefore, a synergy of paraffine and diatomite in suppressing the disadvantages and maintaining the advantages of both components is proposed, in order to reach a win-win situation from the combination of cementitious material, diatomite, and PCM, taking advantage of pozzolanic reactivity and porous feature of diatomite. To elucidate the above-hypothesized synergy, the pozzolanic reaction of the diatomite-PCM composite in saturated calcium hydroxide solution and in cement paste have been examined; moreover, the effects of PCM loading on the flowability, microstructure, and thermo-mechanical properties of paste have been investigated.

Recent advances in mechanical energy harvesting and its applications in structural health monitoring and control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL VALIDATION OF A PROTOTYPE SELF-POWERED STRUCTURAL CONTROL SYSTEM

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ABSTRACT

Self-powered systems are novel control technologies that fully power their operation via the harvesting, storage, and reuse of energy from exogenous disturbances. In the context of structural control, such systems are attractive as they do not rely on any external power supply, which may be unreliable during extreme events such as earthquakes. The most basic example of a self-powered control system consists of an electromechanical transducer embedded within a vibratory system and connected to an energy storage subsystem (e.g., a supercapacitor, battery, or mechanical flywheel). In this configuration, the transducer can absorb energy from the vibrating structure, store that energy, and then intelligently re-inject that stored energy at a future time to reduce the vibratory response. The synthesis of feedback control laws for use with self-powered systems is challenging, as they must explicitly account for parasitic losses in the transducers, power electronics, and energy storage subsystem.

We employ real-time hybrid simulation (RTHS) to experimentally validate a bench-scale, prototype self-powered structural control system. RTHS is a cyber-physical testing method that interfaces numerical models with physical experiments in real time. In the RTHS method, a structural system is partitioned into so-called numerical and physical substructures. Actuators and sensors are used to enforce both displacement compatibility and force equilibrium at the substructure coupling points. In this work, the physical substructure consists of our proof-of-concept, self-powered control system, and the numerical substructure is a 2-DOF shear building model with a tuned-mass-damper (TMD) located on the top floor. The TMD is actuated by an electromechanical transducer, which consists of a permanent magnet synchronous machine (PMSM) coupled with a linear ballscrew actuator. The force produced by the transducer is controlled by regulating the currents in the PMSM. This current tracking is facilitated by a power-electronic drive known as a three-phase inverter. An aluminum electrolytic capacitor is used as the energy storage subsystem. A half-bridge DC-DC converter is used to facilitate bidirectional power flows to and from the capacitor. We assume the exogenous disturbance is an earthquake ground motion, modeled as filtered noise with known spectrum. We validated both linear and nonlinear self-powered feedback controllers. The feedback control laws, along with the numerical substructure are implemented in Simulink on a dSpace DS1103 rapid prototyping system. The performance of these controllers is shown to be superior to that achievable with optimal viscous damping. In addition, the experimental results are found to be consistent with simulation results.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RESILIENT POWER SYSTEMS IN A CHANGING CLIMATE: ADAPTIVE REPLACEMENT STRATEGIES FOR UTILITY STRUCTURES

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[1]The Ohio State University

ABSTRACT

Climate change poses escalating challenges to the built environment worldwide. Increased frequency and intensity of extreme weather events, driven by climate change, are increasing risks to critical infrastructure systems beyond currently acceptable levels. Among the essential infrastructure systems are power distribution networks that deliver electricity to a diverse group of users. The reliability and resilience of this system, consisting of substations, transformers, and low voltage power lines, is crucial for societal welfare and economic stability. Indeed, during and in the aftermath of hazards, a stable electricity supply becomes a lifeline, providing uninterrupted power to critical services such as hospitals, emergency operations, and public facilities. Despite scientific evidence indicating an escalation in natural hazards due to climate change, engineering standards and practices generally assume that extremes of climate and weather will remain stationary for the foreseeable future. Similarly, existing risk assessment approaches for power grids primarily utilize historical climate data, which fail to fully capture the evolving impacts and uncertainties associated with climate change. In the United States, most distribution networks rely on wooden utility poles, maintained through a strength-based wood pole replacement methodology that overlooks evolving climatic risks. Prior research has explored the vulnerability of these poles under specific climatic conditions and the significance of their failure. Still, these studies are typically limited to short-term analyses, lacking consideration of long-term climate dynamics. Consequently, there is a need to develop methodologies that evaluate the long-term influence of climate change on power grid resilience and formulate climate-adaptive replacement strategies for sustained grid performance. The purpose of this paper is to present a novel model for assessing the impacts of pole replacement strategies in the context of climate change. This model employs a key replacement index: the Annual Expected Outage Reduction (EOR), addressing the long-term and short-term effects of pole replacements, respectively. It considers a range of factors, including reactive-proactive replacement, pole aging, upgrades, and the influence of climate change on power grid resilience. The effectiveness of the model is demonstrated with a real-world power grid in Harris County, Texas. This grid consists of 7,051 poles, three substations, and 115 protective devices. Over a 70-year horizon, the performance of the model is assessed under a variety of climate change scenarios. Key findings highlight the necessity of pole upgrades in response to varying climate change conditions. This suggests a strategic requirement for maintaining a diverse inventory of pole types, enabling adaptive responses to regional climatic variations.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AUTOMATED MAPPING OF HUMAN-HUMAN AND HUMAN-INFRASTRUCTURE INTERACTIONS TO SOCIAL BENEFITS USING PRIVACY-PRESERVING SENSING

Cheyu Lin[1] and Katherine Flanigan[1]*

[1]Carnegie Mellon University

ABSTRACT

Cyber-physical systems (CPSs) leverage ubiquitous sensing and control to enhance the performance of infrastructure systems. While CPSs have revolutionized infrastructure management across all economic sectors, possible human-centered, or “social”, benefits (e.g., sociability, productivity) stemming from human-infrastructure interactions have not been well studied. For example, the design of public infrastructure can enhance social capital by providing a place to nurture social ties, contributing to residents’ sense of belonging and community. The state of infrastructure is intimately coupled with, and capable of exercising impact on, social benefits. Very little research has been devoted to modeling the representations that define the interdependencies of infrastructure and social capital. Our presentation focuses on underpinning this modeling via the mapping between social interactions and benefits—namely the functional relationship assigning the extent of social benefits to interactions. Existing work aims to achieve this by qualitatively ordering the level of social benefits of classified social interactions, which confines the capability of algorithms due to the innumerable nature of social interactions and fine-grained nuances of interactions. The existing literature also does not consider the challenge of maintaining privacy integrity during monitoring in such inherently social—and often public—spaces. We present a formalization for the data-driven mapping between human-human and human-infrastructure interactions and social benefits using latent generative landscapes as maps of social capital. Supporting the model is the privacy-preserving depth data of twelve nonverbal dyadic behavioral interactions (1,200 instances total) collected across three different locations—outdoor, confined indoor, and open indoor—at Carnegie Mellon University.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING THE IMPACT OF CLIMATE CHANGE ON THE RISK OF WIND DISASTER: A REGIONAL STUDY OF METAL ROOFS AND POWER NETWORKS IN TAIWAN

Yu-Kai Chuang[1] and Chi-Ying Lin[1]*

[1]National Yang Ming Chiao Tung University

ABSTRACT

This study, based in Taiwan, examines the escalating regional vulnerability of metal roofs and power networks to wind disasters, with a particular focus on how climate change intensifies these risks. In Taiwan, typhoon events predominantly damage non-structural elements and auxiliary facilities, such as metal roofs, water towers, signs, and utility poles, rather than the main building structures. The research aims to conduct a comprehensive wind risk analysis for a specified region, assessing the susceptibility of commonly used metal roofs and power poles to wind-induced harm. This involves a detailed examination of each system's vulnerability, along with an evaluation of the subsequent collateral damage when metal roof failures impact the power network.

Incorporating climate change considerations, the study develops models for wind pressure-demand, load capacity, and exposure specific to metal roofs and power networks. These models consider the anticipated changes in wind patterns and intensities due to climate change. Monte Carlo simulations are employed to generate vulnerability curves, with the metal roof wind pressure model deriving from pertinent design standards. The load capacity model for metal roofs utilizes machine learning techniques, including Random Forest and XGBoost, and is based on experimental data. For identifying and locating regional metal roofs, a deep-learning U-Net image segmentation model is applied to satellite imagery.

Regarding power networks, wind vulnerability curves sourced from related research are adapted to reflect potential changes in wind disaster scenarios under climate change conditions. These curves initially determine the destruction status of individual power poles in the study region, leading to simulations of the overall regional power network's vulnerability at various wind speeds. The exposure model for the power network, which includes the distribution of utility poles and the construction of the power distribution network using Minimum Spanning Tree algorithms, is informed by data from government agencies.

Additionally, the study introduces a trajectory model for projecting the movement of wind-displaced thin objects, such as metal roofs. This model estimates the risk of wind-damaged metal roofs being dislodged and impacting power cables, thus leading to subsequent damage to the power network.

The findings aim to provide crucial insights for prioritizing reinforcement and adaptation strategies for regional metal roofs and power networks in the face of evolving wind disaster risks exacerbated by climate change. By examining the interaction between metal roofs and power networks under extreme weather scenarios, this study can provide guidance for infrastructure system reinforcement strategies.

EFFECT OF FIBER CONFIGURATION ON MECHANICAL BEHAVIOR OF FIBER-EPOXY COMPOSITES THROUGH COMPUTATIONAL ANALYSIS

Yizhou Lin[1], Junyi Duan[1], Chengcheng Tao[1] and Ying Huang[2]*

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ABSTRACT

Composite materials are a class of advanced materials widely used in civil and infrastructure applications because of their unique properties such as high strength, lightweight, high fracture toughness, and long-term corrosion resistance. Composite materials consist of fibers, typically made of carbon, glass, or aramid, embedded in an epoxy resin matrix. Physical testing with trial and error requires substantial time, labor, and material resources to achieve optimal mechanical behavior by fully considering the potential configurations and morphology of superior composite materials. The composite research community has long sought to eliminate these requirements through efficient simulation and optimization. Advances in computational modeling have led to the creation of virtual testing. The objective of this study is to computationally investigate the mechanical behavior of fiber-epoxy composites with various fiber configurations. In this study, we conduct the micro-scale finite element analysis (FEA) for fiber and matrix in composites and run batch simulations for enhanced computational efficiency. A parametric study is performed to investigate the effect of fiber configuration on the strength of the composites. The configuration parameters include fiber volume fraction (ranging from 0.5% to 9.5%), fiber orientation (ranging from 0° to 90°), fiber types, and fiber dispersion rate. Both single and coupling effects are analyzed to explore the impact of various fiber configuration conditions on composite strength. The simulation results show that the composite strength improves with higher fiber volume fraction in isotropic materials. However, single-parameter analysis is not sufficient to investigate the complexity of fiber-epoxy composites. Multi-parameter analysis reveals complex interdependencies among various parameters, offering insights into factors affecting the composite strength. For example, with the increase of the fiber volume fraction and orientation, the strength of composites doesn’t exhibit obvious improvement, caused by the coupling effect from the two parameters. Moreover, composites with higher fiber concentration and less dispersion result in reduced strength when the fibers are oriented at 45 degrees. This study demonstrates the capability and efficiency of micro-scale composite FEA with batch jobs in investigating the effect of complex fiber configurations on composite materials. The research outcomes could provide the composite material community with guidance and user-friendly tools for designing adapted fiber-epoxy composites efficiently.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A COMBINED WEIGHTED VORONOI TESSELLATION AND RANDOM FIELD APPROACH FOR MODELING HETEROGENEOUS ROCKS WITH CORRELATED GRAIN STRUCTURE

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ABSTRACT

Construction rocks often exhibit a grain structure with spatially correlated grain formations, posing a challenge in quantifying and predicting their mechanical properties. Effectively quantifying and predicting the mechanical and fracturing behaviors of these construction materials is crucial for enhancing their exploitation and utilization efficiency. Misjudgments in this regard could lead to unacceptable fractures or even the collapse of rock formations during infrastructure constructions. This work proposes an approach that combines weighted centroidal Voronoi tessellation (WCVT) and random field (RF) to generate heterogeneous rocks with a correlated grain structure. WCVT is used to partition a rock domain into grains, and RF is adopted to control the grain sizes and the size correlation. With rock samples generated based on RF-WCVT, the finite discrete element method (FDEM) is introduced to simulate the mechanical behavior (typically the fracturing behavior) of heterogeneous rocks. The procedure for importing RF-WCVT-based rock samples into an FDEM model and inserting zero-thickness cohesive elements for modeling potential fractures is developed. Numerical examples are presented to demonstrate the effectiveness of RF-WCVT for generating heterogeneous rocks with a correlated grain structure, as well as the performance of FDEM in modeling the mechanical behavior of heterogeneous rocks. Effects of grain structure, in terms of scale of fluctuation and bedding orientation, on the mechanical behavior of rocks are analyzed.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SENSOR DEVELOPMENT AND CHARACTERIZATION FOR POST-WILDFIRE WATER RECOVERY

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ABSTRACT

Recent wildfire events in California and Oregon have resulted in localized water contamination. A potential cause is the heating of polymer-based water service lines when homes have ignited within the communities. Identifying sources of contamination and developing sampling protocols can be a huge burden on municipalities, taking significant resources and time. The investigation in Santa Rosa and Paradise, California too approximately a year and millions of dollars. The delayed access to potable water within the community delayed recovery of houses and businesses. These events highlight the need for a rapid and efficient methodology to know when service lines have exceeded threshold temperature thresholds and replacement of the pipe is necessary. Previous research has shown that the threshold temperatures that result in contamination are 194 ºC for polyvinyl chloride (PVC) and 250 ºC for high-density polyethylene (HDPE) pipes, respectively. The objective of this work is the development of a low-cost sensor system to identify potentially damaged pipelines and sources of water contamination within a community after a wildfire.

The proposed solution is an RFID-based temperature sensor to indicate once a certain temperature is reached. Passive, ultra-high frequency (UHF) RFID tags are used in conjunction with a trigger mechanism that disconnects after the threshold temperature is reached over a meaningful duration. Passive RFID tags will allow for the system to operate without the use battery and are very affordable. The design and characterization of the sensor utilizes three experimental frameworks: (1) benchtop testing, (2) small-scale tests in a more realistic environment, and (3) larger-scale tests under the transient conditions of an experimental fire. The benchtop testing identifies the trigger temperature, mechanism, and reliability of the sensor design. The small-scale testing installs the sensors on buried pipes subjected to a realistic fire load. The large-scale testing extends the small-scale soil-box framework to assess the temperatures buried infrastructure located near a burning house may reach and the viability of the sensors designed in a realistic fire environment. The resulting design and characterization will be presented in terms of accuracy, durability, and reliability. Additionally, the heat flux of the benchtop testing and small-scale tests will differ from a more realistic environment, so the results will be compared to isolate how the flux might impact future WUI-based sensor development.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TAILOR THE BUCKLING RESISTANCE OF A THIN-WALLED TUBE FILLED WITH A GRANULAR LATTICE BY PRESTRESS

Chao Liu[1], Byung Wook Kim[1], Mehdi Zadshir[2] and Huiming Yin[1]*

[1]Columbia University
[2]PVT Clean Energy

ABSTRACT

A novel method is presented to tailor the buckling resistance of a composite column by changing the prestress. The column is made of s a thin-walled tube filled with pressurized particles as a granular lattice . This innovative design creates an adaptable means to change the critical global buckling load by simply tuning the prestress level. Experiment using thin-walled aluminum cylinders filled with steel balls, demonstrate the substantial effect of prestress on the overall buckling behavior. The pressure between particles induces stretching in the tube. The granular lattice core exhibits increasing effective stiffness with the load, which increase the resistance to both the local buckling of tube and the global buckling of the overall column.

To comprehensively analyze the stiffness change and the buckling enhancement mechanism resulting from prestress, this study employs the singum model to predict the elastic behavior of the granular lattice. in which the Wigner-Seitz (WS) cell is constructed as a continuum particle and provided a closed-form prediction of effective elasticity under varying stress conditions. The model also takes into account the deformation of the WS cell under external loads.

For example, a case study of a composite column with a body-centered cubic (BCC) lattice is conducted to ,illustrate how prestress significantly influences the behavior of the lattice structure.

Overall, this work presents an innovative design approach to tailor the buckling resistance and stiffness of columns filled with a granular lattice by controlling the prestress level. These findings will be extended to the optimization of composite structures in various engineering applications.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING THERMOELASTICITY AND FAILURE OF POLYCRYSTALLINE MATERIAL USING A NOVEL NONLOCAL LATTICE PARTICLE METHOD

Di Liu[1] and Hailong Chen[1]*

[1]University of Kentucky

ABSTRACT

The utilization of polycrystalline materials across various engineering applications, including micro components in nano-manufacturing, fuel cells, and electronic sensors, has underscored the importance of understanding their physical behavior under various conditions. To this end, numerous computational methods have emerged for studying the mechanical behavior of polycrystalline materials, including peridynamics, phase field modeling, cohesive zone models, and lattice particle method. Compared to mesh-based methods, the recently developed lattice particle method is a nonlocal meshfree method. The lattice particle method possesses the following features regarding modeling polycrystalline materials. Firstly, the grain domain is discretized into discrete material particles that are regularly packed according to the material underlying atomic lattice. Each material particle interactions with neighboring material particles up to the second nearest neighbors. Secondly, integro-differential equations instead of partial differential equations that used in the continuum-mechanics-based approaches are developed to model the physical behavior of discrete material particles. This circumvents singularity issues inherent in the continuum-mechanics-based approaches when spatial discontinuities exist. Thirdly, the property anisotropic of crystalline materials are explicit captured using lattice rotation instead of transformation of coordinate system that conventionally being used for modeling anisotropic materials. Thirdly, as a direct result of lattice discretization and rotation, mesoscale grain boundary and its effects can be explicitly modeled in the lattice particle method for polycrystalline materials.

In this presentation, the recently developed thermoelastic model using lattice particle method for single grain will be extended to study the thermoelasticity and failure of polycrystalline materials. Details of the construction of discrete particle system for polycrystalline materials will be presented. The development of thermoelasticity model will be reviewed. Equivalence assumptions to the continuum mechanics models will be discussed, including the equivalence of strain energy density, heat transfer rate and thermal strain for mechanical, thermal and thermal-mechanical coupling, respectively. Bond-based failure criterion will be applied to investigate the different failure mechanisms of polycrystalline materials. Comparative analyses of predicted displacement field and temperature field against solutions from other numerical methods will be conducted. Conclusions and future work will also be discussed.

THREE-DIMENSIONAL PAVEMENT RESPONSE MODELING USING GRAPH NEURAL NETWORK

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[1]University of Illinois Urbana-Champaign

ABSTRACT

Three-dimensional (3D) finite element (FE) methods are commonly applied to predict pavement response to vehicular loading and to simulate tire-pavement interaction. However, 3D FE modeling usually is computationally expensive. Hence, an accurate method, but computationally inexpensive is needed to predict pavement responses. This study proposed a graph neural network (GNN)-based method for 3D pavement response modeling. The 3D pavement FE model was represented as a graph by utilizing nodes for FE nodes and edges for connections of FE nodes. These nodes and edges captured data about pavement structures, pavement responses, tire contact stress, continued moving loading, layer interactions, and optimized mesh discretization. An extensive 3D FE database (over 700 3D FE cases) was used to build the dataset for training and evaluating the proposed method, considering different pavement structures, tire types, pavement materials, and temperatures. The proposed GNN-based method has three components: Encoder, Processor, and Decoder. Accurate pavement responses (displacement, stress, and strain) were predicted. Compared to 3D FE pavement modeling, the proposed model significantly reduces computational time, while maintaining the 3D FE accuracy.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING FRACTURE PROPAGATION WITH THM COUPLING EFFECTS IN POROUS MEDIA

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ABSTRACT

This presentation introduces an enhanced strain finite element framework designed for simulating fracture propagation in saturated thermoporoelastic media. The proposed method integrates classical thermoporoelasticity theory with a cohesive fracture model to capture the interrelated behaviors of fluid flow, heat flow, rock deformation, and fracture propagation. Fractures are represented using constant strain triangular elements enriched with constant displacement jumps. The numerical framework is validated through various examples, encompassing scenarios without fractures, cases featuring rigid and deformable fractures, and hydraulic fracture propagation with thermal effects. Results indicate that thermal stress primarily impacts the region near the injection point but has a limited effect on fracture length evolution and fluid pressure distribution within the fracture. Conversely, temperature-dependent viscosity notably influences hydraulic fracture propagation. This work enhances our comprehension of hydraulic fracture modeling in thermoporoelastic media and provides a valuable tool for simulating hydraulic fracturing processes while considering thermal effects.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TIME-DEPENDENT PROPERTIES OF CORAL SAND UNDER TRIAXIAL STRESS STATES

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ABSTRACT

Time-dependent effects of soils have been widely recognized as one of the key issues in geotechnical engineering, which is particularly evident for coral sand due to its high frangibility. To determine the time-dependent behaviors of coral sand under triaxial stress states for enhanced engineering applications, a series of triaxial tests was carried out on coral sand using two particle size distributions. Besides the conventional time-dependent tests, deviator-stress rate, creep with different stress history, drop creep/relaxation and post-peak creep/relaxation tests, which have been rarely investigated, have also been conducted. Additionally, the particle size and shape variations in the coral sand after the tests were analyzed to elucidate the time-dependent behavior mechanism. According to the test results, over- and under-shooting phenomena were not clear when the deviator stress rate changed suddenly, while it is evident with varying strain rate. Creep behavior was found to be noticeably influenced by the stress history and decreased with increasing pre-consolidation pressure. The stress-unloading could considerably reduce the subsequent creep or relaxation response, and the response diminished with increasing magnitude of deviator stress drop. The time-dependent behavior of coral sand was mainly determined by the level of particle breakage. The coral sand particles became smaller and more regular due to particle breakage, which would increase the compressibility of specimens and weaken interlocking between the sand particles, leading to more obvious time-dependent behaviors. The influence of particle breakage on the time-dependent behaviors of coral sand could be examined from two perspectives, i.e., the particle breakage during creep or relaxation processes and that during pre-loading processes. The effects of the unstable broken particles that formed during pre-loading were larger. In addition, a unique relationship was observed between the relative breakage and input energy for the same coral sand type, regardless of the test conditions, which was meaningful for the time-dependent constitutive modeling considering particle breakage.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BIO-SYNTHETIC HYDROGEL-BASED CONCRETE (BIO-HBC) FOR CONSTRUCTION ON MARS

Ning Liu[1], Wenwei Huang[1], Shing Chi Lam[1], Qikun Yi[1], Fei Sun[1] and Jishen Qiu[1]*

[1]Hong Kong University of Science and Technology

ABSTRACT

Concrete production on Mars presents unique challenges due to the planet's low temperature and atmospheric pressure, which limit the availability of liquid water for the hydration of hydraulic binders. In previous studies, we have demonstrated that hydrogels can be used as sand binders to make concrete under Mars-like conditions. In this study, we explore the use of genetically modified yeast strains (S. cerevisiae) to synthesize hydrogels to produce bio-HBC. These modified microbes are capable of generating recombinant SpyTag/SpyCatcher pairs and MFPs, which enable the hydrogels to achieve strong cohesion within themselves and strong adhesion to sand simultaneously. Our bio-HBC prototypes were cured in a Mars-like environment (-55°C and 0.001 atm) and achieved a compressive strength of 2.5 MPa, sufficient for supporting a dome structure on Mars. To further enhance the mechanical properties of bio-HBC, we developed a hybrid version by mixing bio-hydrogel with artificial hydrogel, resulting in a compressive strength of 12 MPa. This improvement is attributed to the effective chemical combination of adhesive proteins and artificial gel, as well as the formation of a reinforced microstructure. The yeast strains used in this study were able to survive in extreme conditions, and the hardened gel in bio-HBC mother bricks was successfully recycled by warm water and mixed with new sands to produce child bricks with mechanical strength higher than 60% of the mother bricks. Additionally, the SpyTag/SpyCatcher protein system used in this study has the potential to be used as a plugin for connecting functional proteins to achieve desired properties, such as anti-freezing and anti-radiation capabilities. Our findings demonstrate the potential of using genetically modified yeast strains to produce bio-HBC for construction on Mars.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRAPH NEURAL NETWORKS FOR ASSESSING IMPACTS OF EXTREME EVENTS ON REGIONAL MOBILITY

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ABSTRACT

To prepare regional transportation networks for extreme events, it is critical to establish a proper asset management framework. This framework improves resiliency by using predictions of the conditions of a regional network under likely emergency scenarios. Advances in computational science and engineering can enable decision makers to use computational asset management frameworks that not only quantify the conditions of the network assets but also the emergent traffic dynamics in these scenarios. To this end, we have proposed graph neural network (GNN) models for efficient and accurate modeling of large-scale regional networks. In the past, we showed how these models can predict network connectivity and shortest distances between different nodes in the network. In this presentation, will present a GNN model for the estimation of travel time, by offering a surrogate for the traffic assignment problem. This model is generalizable to various extreme events and various network topologies. Using numerical examples, we show how this model can be used as a mobility-aware decision support for resilience management of transportation networks.

PROBABILISTIC MODELING OF OPTIMAL PLACEMENT STRATEGIES OF HAZARDOUS MATERIALS RAILCARS IN FREIGHT TRAINS

Chen-Yu Lin[1], Xinhao Liu[2] and Christopher Barkan[2]*

[1]National Yang Ming Chiao Tung University
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ABSTRACT

Railcars transporting hazardous materials (hazmat) are subject to differing probabilities of involvement in a derailment depending on their position in a train. This effect is particularly important in long-freighttrains characteristic of North American operation. For decades industry and government have considered whether operating practices and regulations should account for this in order to reduce the probability of hazmat cars derailing.

This paper presents a position-dependent, railcar-based model to analyze derailment probability of hazmat cars and identify optimal placement strategies that minimize the expected number of hazmat cars derailed. The method considers derailment probabilities of each hazmat car at each position in a train and investigates the optimal placement of hazmat cars given train makeup, speed, and the number and percentage of hazmat cars in a train. A case study based on realistic train configurations and operational conditions is presented, and a sensitivity analysis is conducted that explores the effect of key factors on placement strategies. The results indicate that there is no single placement strategy that minimizes hazmat car derailment probability under the variety of characteristics typical of North American freight train operation. This result has implications for rail hazmat transportation safety, operations, efficiency, and regulatory policy. This research advances our understanding of the effect of hazmat car placement on operating safety and risk and enables development of holistic quantitative models to address the trade-off between hazmat train operating safety and efficiency that accounts for both mainline derailment severity and yard activities related to train make-up.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TIME-DEPENDENT DEFORMATION OF SOIL DURING FREEZING AND THAWING PROCESSES

Yingxiao Liu[1] and WaiChing Sun[1]*

[1]Columbia University

ABSTRACT

Ground heave and settlement caused by freeze-thaw cycles is one of the main considerations of engineering design in cold regions, but predicting such deformation over time remains a great challenge in practice due to the coupled thermal-hydro-mechanical (THM) processes involved in it. Previous studies usually treated ice as a second fluid phase in soil which stays in equilibrium with water and exhibits no mechanical deformation, but numerous experiments have revealed that both ice and ice-soil mixture can bear significant shear load and develop large creep strain. This work aims to investigate the time-dependent deformation of water-ice-soil system by combining multiple time-dependent processes including hydrodynamic lag, phase transition, and the creep of both ice and soil. We derive and verify a new constitutive model where ice is treated as a second solid phase forming a skeleton and deforms continuously when loaded. The phase transition between ice and water is modeled in a kinetic way based on thermodynamic equations. Further THM finite element simulations are conducted on both laboratory and field samples under freeze-thaw cycles from hours to months, and numerical results show good consistency with experimental and field records on both scales. The model provides insights into different time-dependent processes involved and allows the separation of their effects over different stages.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOWARD GREEN AND INTELLIGENT TRANSPORTATION INFRASTRUCTURE: A NOVEL DOUBLE-YOLOV7 NETWORK AND DATA AUTOAUGMENT FOR ROAD CRACK DETECTION FROM CCD AND GPR IMAGES

Zhen Liu[12], Bingyan Cui[3] and Shihui Shen[4]*

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[4]Pennsylvania State University, Altoona

ABSTRACT

Pavement distress detection is a crucial component of its structural health monitoring (SHM) systems. Of all the distresses, cracks, as the mostly emerged distress, seriously affect the remaining life and driving safety of transportation infrastructures. However, accurate and rapid identification of pavement cracks detected by vehicle-borne charge-coupled devices (CCD) and ground penetrating radar (GPR) still faces numerous challenges.

Therefore, two improved you only look once version 7 (YOLOv7) models were proposed for detecting pavement surface crack (CKs) and internal crack (CKi). The acquired crack images were augmented using the Fast AutoAugment strategy based on density matching and Bayesian optimization. According to the imputation analysis of the original YOLOv7 detection results, the EfficientnetV2 network and coordinate attention (CA) attention mechanism were integrated into the backbone structure, and the BiFPN network was used to expand the receptive field for the CKs model; As for CKi model, a small detection layer and CA-based MaxPooling (MPCA) module were added for reduced the information loss during sampling stage. In addition, anchor sizes were optimized using an improved K-means algorithm, and the SIoU loss function was conducted for more stable convergence and smaller prediction errors in the proposed Double-YOLOv7 network. Experimental results illustrated that the average precision (AP) and F1 score of the CKs model were 90.6% and 90.1%, which were 4% and 3.9% higher than the original YOLOv7, and that of the CKi model was 89.4% and 89.8%, which were both increased by 3.7%. Inference time of the CKs and CKi model were 15.38 and 20.64 ms on a Tesla V100-PCIe-32 GB GPU, respectively. The major contributions in this research are summarized as follows:

1) An improved Double-YOLOv7 network is proposed for pavement crack detection.
2) A Fast AutoAugment strategy was used to find the optimal augmentation operations.
3) Feature enhancement and attention mechanism were performed to improve the recognition accuracy.

Overall, the proposed method was effective and suitable for industrial application and promotion. In future works, we can further analyze the feature sharing between the two networks, integrate the improvement measures into a single network, and further promote the application of the model.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC LEARNING ON MANIFOLDS (PLOM) FOR SEISMIC RESPONSE OF CONCRETE BRIDGES IN REGIONAL HIGHWAY NETWORKS

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ABSTRACT

Understanding the performance of a regional bridge stock is an integral part of planning for the design, retrofit, and post-earthquake recovery of transportation systems. This research focuses on the development and implementation of high-fidelity simulations of bridge performance using the Probabilistic Learning on Manifolds (PLoM) method, developed by Soize and Ghanem (2016). With the ultimate goal being to provide a computationally efficient means to assess seismic performance of a regionally distributed highway network, the PLoM model is trained using results of nonlinear structural analyses to estimate bridge response for target structural and ground motion parameters.

Two major focuses characterize this work, the first being the development of an efficient and generalizable process to determine two PLoM hyperparameters that are used in diffusion-maps to control the model complexity. In this method, “quasi-stripes” of structural response data, selected at various earthquake intensities, are used to tune hyperparameters at various ground motion intensity levels. These tuned hyperparameters are then used to develop an intensity-based interpolation for estimating the response of bridges to regional earthquake hazard parameters.

The second major focus is to compare PLoM with other methods for regional seismic assessment of bridge performance. In addition to comparisons with response data from detailed OpenSees models, the PLoM results are also compared with an estimate from a Gaussian Process (GP) model. The models are compared by assessing the performance of archetype bridges in the San Francisco Bay Area under ground motions corresponding to the HayWired M7 Earthquake Scenario (USGS, 2018). At each site, spatially-correlated ground motions are run through OpenSees models corresponding to specific bridge designs to generate a “ground truth” dataset. The two surrogate models are then assessed using the same ground motion and structural input data as was passed into the OpenSees model. Validation is done by directly comparing the bridge response parameters from the OpenSees models to those predicted by the PLoM and GP models. After generating response parameters using the OpenSees, PLoM, and GP models, results are passed into Caltrans fragility functions to evaluate the loss predictions. This study compares the accuracy of the predictions from each model, as well as ease of use, dimensionality, input and output distribution capabilities, and limitations of the models.

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Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ASSESSMENT OF THE VIBRATION MITIGATION PERFORMANCE OF SEISMIC METASURFACES ON LAYERED SOILS BY MEANS OF POWER FLOW

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ABSTRACT

Although rail is a sustainable and climate-friendly means of transport, vibration remains a particular environmental concern. Mitigating vibration induced by dynamic axle loads remains challenging for the following reasons: 1) the train consists of a large number of axles, which each contribute with different directionality to the total wavefield; 2) vibration mitigation in a wide frequency band is needed; and 3) in layered soils, vibration propagates as a superposition of multiple dispersive surface waves.

We investigate how seismic metamaterials on the transmission path between track and buildings can mitigate railway induced vibration in a wide frequency band (1 - 80 Hz). Particular focus is on layered soils where the vibration reduction resulting from the metasurface is non-uniform. The metasurface consists of an array of local resonators, arranged on a uniform grid at the soil's surface. As a global performance metric, we compute power flow [1,2] through a vertical surface in the soil behind the metasurface. A 3D finite element - boundary element (FE-BE) formulation is used to model the interaction of the metasurface with the soil [3].

To achieve broadband vibration mitigation, arrays of resonators with graded resonance frequencies are considered. First, a classical metawedge is studied, where the vibration reduction relies on rainbow trapping. In this case, the power dissipated by the resonators is high, while the power flow over the virtual screen is low. Second, the case of an inverse metawedge is considered. When compared to the case of classical metawedge, the dissipated power by the resonators is lower, while the power flow over the virtual screen is higher. This result indicates that surface waves are converted to body waves by an inverse metawedge. These body waves are partially trapped within the layer decreasing their vibration mitigation performance. The results of the two cases suggest that the classical metawedge may be more suitable for vibration mitigation of ground vibration produced by railway traffic.

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Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND RESPONSE ANALYSIS OF A PROTOTYPE FRAME WITH UNBONDED FIBER-REINFORCED ELASTOMERIC-ISOLATORS

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ABSTRACT

Seismic mitigation is currently the need of the hour due to the constant reminder for better and more resilient structures posed by several historical and recent major seismic events. Base isolation has turned out to be an excellent, cost-effective, and efficient candidate for this purpose in recent times. Unbonded fiber-reinforced elastomeric isolators (UFREI), a relatively recent introduction to the family of rubber isolators, consist of alternating layers of elastomers and fibers stacked together with no bonded contacts to the superstructure and substructure. These modifications to conventional steel-reinforced elastomeric bearings improve its efficiency and cost-effectiveness against seismic hazard.

Although isolation devices are very effective for mitigation of seismic action, they may cause serviceability and habitability issues under wind loads due to the proximity of the isolated structure's period to the pulse periods present in wind excitations. Because of their additional flexibility due to rollover, UFREI performance under wind loading still needs to be properly investigated. High isolator displacements under extreme wind events may raise issues like pounding and residual displacements while frequent events may cause fatigue phenomena. Hence, a prototype 2-storey RC frame base isolated with UFREIs - preliminary designed according to seismic action in a medium-high seismicity region - is properly modelled and subjected to wind loads. The performance of the base isolation system under different hazard levels is investigated providing useful insights.

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING AND IMPLEMENTING ALTERNATIVE REPAIR AND REPLACEMENT STRATEGIES FOR WATERWAY INFRASTRUCTURES

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ABSTRACT

In the early to mid 1900's, the United States heavily invested in it's inland waterway systems and constructed the majority of its hydraulic steel structures (HSS). Therefore, over 80% of the HSS are well over their design life, leading to deteriorated design boundary conditions that result in overloads and unsatisfactory performance. The current repair and replacement methods are primarily adopted from the bridge industry, slow in fabrication, difficult to implement, and may not provide sufficient life increase. It is imperative to investigate alternative repair and replacement materials and methods. In this presentation, some of these alternatives include patching methods with fiber reinforced polymers and additive manufacturing with metals, polymers, and mixed materials will be presented. The ability of these materials and methods to extend the design life or provide time to fabricate and replace sections of the HSS will also be discussed.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FOUR-DIMENSIONAL PREDICTION OF GEOLOGICAL CARBON SEQUESTRATION USING FOURIER-DEEPONET

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ABSTRACT

Carbon capture and storage (CCS) is recognized as one of the most effective means to address climate change by reducing CO2 levels in the atmosphere. However, carbon sequestration technologies face significant challenges encompassing economic considerations, identification of storage sites, and the permanence of sequestered carbon. Computational demands associated with large spatiotemporal domains make numerical simulations impractical for multiple forward simulations, hindering the fast adoption of this technology in real-world scenarios. Here, we develop a deep learning model Fourier-DeepONet, which combines the expressiveness of Fourier neural operator (FNO) with the modularity of deep operator network (DeepONet) to address such concerns. Fourier-DeepONet not only exhibits at least twice the training efficiency compared to FNO, a state-of-the-art neural operator but also significantly reduces GPU memory consumption thanks to DeepONet's capability to treat temporal coordinates separately. Fourier-DeepONet yields rapid inferences within seconds for a single reservoir simulation, a four-dimensional scenario encompassing spatial and temporal coordinates. The instantaneous prediction of subsurface conditions, such as pressure buildup and gas saturation, further enables a probabilistic assessment, which was deemed intractable with traditional methods. Furthermore, Fourier-DeepONet showcases commendable generalization capabilities, particularly in extrapolation regimes in terms of temporal coordinates, reservoir conditions, and injection schemes.

DYNAMIC FEEDING-DISCHARGING BEHAVIOR OF MILLED CORN STOVER IN WEDGE-SHAPED HOPPERS

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ABSTRACT

Lignocellulose biomass is one of the most promising resources for producing sustainable aviation fuels as an alternative to fossil fuels. However, the commercialization of bioenergy has suffered from various material handling issues, such as the jamming and unstable flow of milled biomass in handling equipment like hoppers and feeders. Fundamentally, these issues stem from the poor flowability of biomass particles. For example, milled corn stover, one of the most widely used bioenergy feedstock, consists of cobs, husks, leaves, and stalks. These anatomic fractions have very different physical properties, making corn stover particles have a high aspect ratio, irregular shape, complicated surface texture, and high bulk compressibility. These material attributes set corn stover apart from conventional granular materials (like sands) and make it challenging for existing numerical approaches to predict the flow behavior. Recent studies greatly improved understanding of discharge flow behavior in wedge-shaped hoppers pre-filled with biomass. However, a more common situation in practical biorefineries is continuous feeding and discharge, which has not yet been well studied. This work investigates the dynamic feeding-discharging behavior of milled corn stover in wedge-shaped hoppers by combining physical experiments and discrete-element method (DEM) simulations. A graphics processing unit (GPU) computing-enabled open-sourced DEM solver is developed with a bonded-sphere particle model to capture the elongated shape of particles, and a liquid bridge model is implemented to describe the cohesion among particles. Model parameters are calibrated from laboratory-scale benchmark flow tests, and the DEM model is validated by comparing the granular flow behavior against pilot-scale hopper flow tests. Simulations are conducted to evaluate the effects of different feeding methods, feeding rates, and feeding heights on the effective discharge in hoppers with different flow patterns (i.e., mass and funnel flow), outlet sizes, and hopper wall inclinations. We will report the simulation results and propose that the maximum feeding rate to ensure continuous discharge can be described as a function of a few hopper parameters and material attributes. This study promotes the scientific understanding of the dynamic feeding-discharging behavior of milled biomass and sheds light on the development of a modeling-assisted design guide for feeding control to ensure continuous material flow in biorefineries.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DATA-DRIVEN MODELING FRAMEWORK ON THE MECHANICAL BEHAVIOR OF VERTEBRAL BODY

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ABSTRACT

Bone, as a natural architected material, has inspired the creation of numerous engineered architected microstructures due to its excellent mechanical properties. However, the gradual process of bone degradation and microstructural deterioration associated with aging and health conditions can precipitate the development of osteoporosis, which is particularly prevalent in the vertebral body and may even lead to spine fracture. Hence, exploring the mechanical behavior of vertebrae is of great clinical and biomechanical importance, aiming to assist in the assessment of health performance and facilitate the early detection of diseases. We present here a data-driven framework to model the vertebral body through a local structure-property relationship, which is optimized through the corresponding experimental measurements. A set of samples from L1 vertebrae is first experimentally compressed in a custom-designed chamber under a hydrated environment, and the deformation at each step is measured using microcomputed tomography imaging, compositing the experimental target variables of the dataset from various samples under varying loading conditions. The corresponding numerical model of each sample is constructed from the quantitative computed tomography scanning on the undeformed specimen. Guided by insights from architected materials that relative density is the dominant microstructural feature governing effective material properties, each element is assigned material properties through different artificial relationships with local bone mineral density, compositing the features of the dataset. Subsequently, the experimentally measured displacement fields are applied to the numerical simulations, and the corresponding numerical results are extracted as the target variables of the dataset. Here, starting with stiffness as an illustrative property and using an energy balance criterion, the data-driven techniques are employed to 1) derive the correlation between the applied artificial modulus-density relationship and the numerical strain energy, and 2) find the optimized modulus-density relationship to align the numerical strain energy with the experimental external work. We will further show how this framework can be used to predict the health of the vertebral body and investigate its correlation with factors such as age and gender.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF A LIGNIN-BONDED BIOCOMPOSITE FROM SAWMILL BY-PRODUCTS

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ABSTRACT

One of the greatest challenges of the 21st century will be using more sustainable building materials on a larger scale, as the current trend towards more timber constructions already suggests. The value chain of wood products starts in sawmills, where logs are sawn into wooden lamellas, the basic elements for modern structural wood-based products, which not only generate immense added value but store a significant amount of carbon dioxide. However, the mean lumber yield in sawing is only about 50 % and becomes even less in further processing steps up to the finished construction. Thus, the greater part of this valuable raw material is fed to low-value chains and even burned to a large extent.

We disassemble these by-products as little as necessary through thermo-chemical-mechanical pretreatment and a gentle extraction process of lignin, hemicellulose, and extractives. Only with an intensity required to obtain individual and highly reactive fibers that can be reassembled using binding materials that are available in the same raw material, like lignin [1,2] or extractives. To achieve this research goal, we use a chemistry-based and simulation-guided development strategy, which needs an interdisciplinary approach with fundamental research in multiple fields. Innovative microscopic and spectroscopic techniques are used in a new interaction to identify the type and location of the bonds achieved, and the biocomposite is described mechanically on different length scales with advanced concepts of continuum micromechanics [3] and finite element-based fracture mechanics.

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Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RARE-EVENT RELIABILITY EVALUATION OF ADDITIVELY MANUFACTURED COMPOSITES WITH HIGH-THROUGHPUT TESTS

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ABSTRACT

Due to the design flexibility, tailored material properties, and cost efficiency, additive manufacturing (AM) of continuous fibrous composites has emerged as a revolutionary technology for composite manufacturing. It has demonstrated the potential to replace expensive and labor-intensive manufacturing processes such as autoclave molding. However, challenges persist in achieving reliability, consistency, and quality in AM composites, which is crucial to aerospace applications. The common concern is that the strengths of the 3D-printed composites are notably lower and scattered compared to conventionally manufactured composites and metals1,2. Therefore, there is a pressing need of quantifying the statistical strength distribution of AM composites. This research demonstrates a high-throughput testing method to efficiently measure the strength distribution of the material especially for the strength data at the lower tail region of the probability distribution.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FIRST-PASSAGE RELIABILITY OF MULTI-DIMENSIONAL NONLINEAR SYSTEM ENDOWED WITH FRACTIONAL DERIVATIVE ELEMENTS OF RANDOM ORDER VIA DR-PDEE

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ABSTRACT

The recently developed dimension-reduced probability density evolution equation (DR-PDEE) approach is extended to solve the first passage reliability of multi-dimensional nonlinear systems endowed with fractional derivative elements. Specifically, the new derivation of the DR-PDEE has extended its applicability to non-Markovian process, and therefore systems with fractional derivatives can be easily treated. Further, an absorbing boundary process (ABP) associated with the response quantity of interest is constructed according to the given failure criterion. Then, the intrinsic drift coefficients (IDC) in the DR-PDEE of the ABP is estimated from a small number of deterministic analyses. Finally, the first passage reliability can be obtained by integrating over the probability density function solved from the DR-PDEE via numerical path integration. Notably, this approach is rather flexible that random system parameters, including even random orders of the fractional derivative elements can be considered. Moreover, the excitation of the system can be either white or non-white, and the type of nonlinearity is not restricted as well. The accuracy of the approach is demonstrated by comparisons with pertinent Monte Carlo simulation results in several numerical examples.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICALLY-DRIVEN DIMENSION-REDUCED PROBABILITY DENSITY EVOLUTION EQUATION

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ABSTRACT

The probabilistic response determination of high-dimensional non-linear stochastic dynamical systems has long been a challenge in sciences and engineering fields. Both the randomness from system parameters, such as the material properties and geometric sizes, and external excitations, such as the earthquake ground motion or wind load, have significant effects on the dynamic behaviors of systems. The newly established dimension-reduced probability density evolution equation (DR-PDEE) provides the governing equation of the evolution of transient probability density function (PDF) for a generic path-continuous response process with the randomness involved in both parameters and excitations, which is a dimension-reduced partial differential equation (PDE) in terms of any quantity of interest. In the present paper, a physically-driven numerical method is developed for solving the DR-PDEE of high-dimensional nonlinear systems involving randomness from both parameters and excitations. For the system under consideration, the random parameters can be independent or de-pendent; the stochastic excitation can be nonstationary and non-white, and modelled as the output of some linear filter to white noise. If the transient PDF of one response quantity of the system is of concern, the DR-PDEE can be established as a one- or two-dimensional PDE, in which the intrinsic drift function is the physical driving “force” for evolution of the PDF. It can be identified via data from a number, in the order of magnitude of hundred, of representative deterministic dynamic analyses. The transient PDF can be obtained by solving the DR-PDEE. An example is illustrated to verify the efficiency and accuracy of the proposed method.

Keywords: Dimension-Reduced Probability Density Evolution Equation (DR-PDEE), High-Dimensional Stochastic Dynamical System, Probabilistic Response Determination, Transient Probability Density Function (PDF), Intrinsic Drift Function.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC NUMERICAL ANALYSIS ON THE FIRE RESILIENCE OF COMPOSITE FLOORS DESIGNED PER PERFORMANCE-BASED APPROACH

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ABSTRACT

Composite steel-frame structures are widely used in the United States. Although their structural fire design is most commonly conducted through prescriptive methods, performance-based structural fire designs (PBSFD) are increasingly considered for their potential to deliver flexible, resilient, and economic solutions. However, comparative assessments on the resilience of composite structures designed per prescriptive and PBSFD methods are limited, particularly under natural fires and considering uncertainties. The National Institute of Standards and Technology (NIST) recently conducted three full-scale fire tests on composite floors which provided unique insights into the fire performance of various designs. The tests provide opportunities for additional computational studies of the fire performance of full-scale composite floor structures, to capitalize on the experimental findings for model calibration and further analyses under realistic fire conditions.

In this context, this study performs a probabilistic numerical analysis of steel-concrete composite floors under natural fires. The objective is to reinforce the adoption of PBSFD, using computational models calibrated on NIST tests. The computational models can successfully predict experimental responses, especially on the vertical displacements and damage patterns in the concrete slab. Different damage states are defined to link the limit states of the composite floor performance and the corresponding post-event functionality and recovery cost. Fragility curves are then developed for the two design methods to quantify the probability of damage states as a function of the fire severity. Results show that the performance-based design using tensile membrane action has a higher probability of moderate damage but a lower probability of integrity failure than the prescriptive design. Parametric analyses show that increasing the amount of slab reinforcement or the amount of axial restraint at the boundaries further reduces the probability of failure. This work contributes to the adoption of PBSFD for enhanced robustness against extreme fire events and advances the resilience of communities to fire. The developed fire fragility functions can help to evaluate the probabilistic performance of various fire designs. It facilitates fire-resilient analysis of steel buildings with composite floors in a community context, aiding in fire loss analysis and comparing the impacts of PBSFD adoption.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ORIGAMI METAMATERIAL WITH ORTHOTROPIC MECHANICAL PROPERTIES

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ABSTRACT

Origami-inspired mechanical metamaterials have recently gained increasing attention in various engineering fields due to their unique physical properties determined by the micro structure geometry. Most origami metamaterials are designed and optimized to reach a specific target such as smooth force response, high energy absorption, while it is difficult for a single origami structure to bear distinct mechanical behaviors simultaneously. Here we propose a novel origami metamaterial which exhibits remarkably different mechanical properties under quasi-static compression. We have demonstrated through experiments, numerical simulation, and theoretical analysis that this newly designed metamaterial is folded in a rigid origami manner when loaded in the x direction, and thus shows low stiffness and specific energy absorption (SEA). When loaded in the y direction, high stiffness and SEA are achieved arising from the non-rigid origami folding mode. In the z-direction, the metamaterial undergoes a rigid origami folding in the beginning followed by a non-rigid one, leading to a graded response. Furthermore, the effects of geometric parameters on the compressive stiffness and SEA are obtained to program the mechanical properties of the metamaterial in each direction. In summary, the proposed orthotropic metamaterial shows great potentials for applications requiring environment adaptation or multi-function.

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCED NATURAL HAZARD ASSESSMENT: NUMERICAL MODELING HURRICANE-INDUCED WAVE PROPAGATION AND ATTENUATION AFTER OVERTOPPING SAND DUNES DURING STORM SURGE

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ABSTRACT

Sand dunes serve as critical natural defenses, shielding coastal communities from the devastating impact of extreme events like hurricanes. This study harnesses the validated non-hydrostatic XBeach model (XBNH) to dissect the dynamics of wave propagation, breaking, and overtopping of sand dunes during Hurricane Michael—a Category 5 storm—at Mexico Beach, Florida. This paper analyzed the varying stages of storm surge, providing a detailed account of the interaction between the surging waves and coastal dunes. The results illuminate the role of sand dunes in mitigating wave forces, revealing a substantial attenuation of wave heights by a minimum of 35% during peak storm surge and an impressive 91% during the upper rising surge stage. The pinnacle of wave height and dune erosion rates were pinpointed around the storm surge's climax. A juxtaposition with the hydrostatic model (XBSB) affirms the XBNH's superior precision, with an average error margin for significant wave height at a mere 2.44%, in stark contrast to XBSB's 16.92%. Additionally, the peak water surface elevation error was significantly lower for XBNH at 3.48% compared to XBSB's 5.39%. These findings not only underscore the efficacy of sand dunes as natural barriers but also elevate the XBNH model's status as a pivotal tool in the accurate assessment and quantification of uncertainties in natural hazard modeling. The study contributes significantly to the predictive monitoring and modeling of coastal hazards, offering a robust framework for enhancing resilience against future hurricane events.

UNSUPERVISED ANOMALY DETECTION FOR INDIRECT STRUCTURAL HEALTH MONITORING UNDER DYNAMIC ENVIRONMENTAL AND OPERATING CONDITIONS

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ABSTRACT

Real-time condition monitoring is essential to understand the health of infrastructure systems, alerting maintainers to abnormalities as they occur. Indirect structural health monitoring (SHM) techniques---which utilize sensors onboard vehicles to detect underlying infrastructure conditions ---have emerged as a promising scalable, non-invasive, and low-cost approach to infrastructure monitoring over extensive inspection areas. However, SHM on infrastructure is subject to everchanging spatiotemporal conditions and poses significant challenges in establishing baselines and obfuscating out-of-distribution (OOD) anomaly detection, the effects of which are exacerbated further in indirect monitoring. Existing research utilizing machine learning algorithms has primarily relied on strategies that bake in training biases (e.g., supervised learning) to detect damage without accounting for the effects of changing environmental and operational conditions (EOCs) on anomaly detection. This oversight hinders algorithmic defect detection in new settings or unknown situations, raising questions about the data requirements, robustness, and generalizability of current solutions for dynamic, real-world applications. While studies using techniques, including sensor networks, testing EOCs one at a time, and knowledge-informed constraints have tried addressing this problem in laboratory testbeds or constrained field tests, their effectiveness in real-world SHM applications still falls short. This presentation widens the stated bottleneck by exploring anomaly origins and sensitive frequency bands in extensive OOD detection operations, a critical problem affecting monitoring methodology in dynamic environments. To contextualize these developments, we introduce this work in the context of broken rail detection. The study utilizes a real-world rail accelerometer and GPS dataset collected from diverse train operating conditions, incorporating data from sensors across a locomotive and serving as a resource for evaluating varying, unknown EOCs. To overcome the challenge of distinguishing unlabeled anomalies, we compare feature extraction techniques, including Principal Component Analysis and Independent Component Analysis, to provide an informed upper bound on the intrinsic dimensionality of Variational Autoencoders. As anomalies resulting from infrastructure damage manifest in specific frequency bands, unsupervised semantic segmentation techniques are applied to the reconstructed frequency to identify subbands containing OOD abnormalities. Finally, spatiotemporal dependencies hidden within the frequency response signal are analyzed using association analysis-based models. Our work advances the field by developing an unsupervised approach for detecting anomalies in dynamic EOCs. Our study introduces a method for real-time condition monitoring that is versatile and applicable across various fields for targeted anomaly detection and explores locomotive frequency response subbands associated with various EOCs and infrastructure damage.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCING THE ACCURACY AND INTERPRETABILITY OF DIGITAL TWINS WITH HYBRID PHYSICS-INFORMED MODELS

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ABSTRACT

Widespread industry adoption of the Internet of Things (IoT) and Artificial Intelligence (AI) has positioned Digital Twins (DTs) to reshape the landscape of modern systems, serving as virtual information constructs mirroring and predicting behaviors of diverse systems to enable informed and automated decisions. However, widespread DT adoption faces several challenges due to the increasing complexity of multi-stakeholder interactions, including among AI experts, system engineers, and data analysts. This complex network of interactions, distinct from the previously linear communication between stakeholders, is critical for facilitating comprehensive system analysis and enabling stakeholders to access diverse sources of information. For example, in the shift towards Predictive Maintenance (PMx), the traditional interactions between asset operators, equipment suppliers, and maintenance teams have expanded to include a wider range of stakeholders such as data scientists and logistics coordinators. Despite multi-stakeholder interactions being central to advanced systems, state-of-the-art DTs struggle to consolidate and present information in interpretable formats to all stakeholders. This can be due, for instance, to overemphasis on the integration of Machine Learning (ML) within DT design, as many DTs are predominantly data-driven with limited incorporation of physics-based knowledge. Among current research, the use of physics-informed data-driven models are popular due to their enhanced model interpretability, which translates complex physical phenomena into formats more accessible for diverse parties to understand and be involved, bridging the technical and application domains and facilitating multidisciplinary collaboration. However, representing physical phenomena as boundary conditions or loss functions can lead to the unstable performance of models when the physical system evolves or deteriorates. We propose a hybrid approach, distinct in its use of an explicit physics-based model alongside a data-driven model, that offers novel advancements in DTs. The explicit physics-based model ensures more comprehensive transfer of insights to the data-driven model, enhancing the overall system’s predictive accuracy and interpretability. Unlike the conventional unidirectional relationship between existing hybrid models, insights from our data-driven model also guide the physics-based predictions, enabling more accurate and high-resolution understanding of the asset’s behavior. We demonstrate this through a pedestrian bridge structural health monitoring (SHM) case study. The bridge serves as a practical example, where we assess the performance of the hybrid model using specific metrics like error rates for accuracy and the clarity of model outputs for interpretability. These quantitative evaluations showcase the potential of our approach in providing reliable and comprehensible insights for diverse stakeholders involved in DT operations.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LARGE DEFORMATION ANALYSIS OF PILE INSTALLATION EFFECT FOR THE OPEN-ENDED PIPE PILE

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ABSTRACT

The simulation of pile installation is a critical undertaking to enhance comprehension of the intricate pile-soil interaction mechanisms and facilitate the rational design of pile foundations. However, achieving this within the framework of three-dimensional (3D) finite element modeling poses substantial challenges, such as large deformation and mesh separation. Currently, two alternative approaches, namely the Arbitrary Lagrangian-Eulerian (ALE) and the Coupled Eulerian Lagrangian (CEL) techniques, are employed in simulating pile installation. However, when dealing with open-ended piles, relying solely on the ALE technique proves insufficient due to its incapacity to handle mesh separation beneath the pile tip during installation. Conversely, the utilization of the CEL technique often entails exorbitant computational costs and inaccurate depiction of pile-soil interaction, given its reliance on a volume fraction to describe the material filling within an element. Addressing the limitations of the ALE and CEL techniques, we employ a novel approach incorporating a zipper technique with the ALE method to simulate the installation of large-diameter open-ended pipe piles into a sand deposit. Our chosen method provides a more precise description of pile-soil interaction with reduced computational costs compared to the CEL technique. Additionally, post-pile installation, a final compression step is employed to establish the pressure bulb beneath the pile tip. The complicated mechanical behavior of the surrounding sand during pile installation is elucidated through an advanced bounding surface sand model. This model comprehensively delineates the evolution of state variables, such as void ratio and shear modulus, as well as stress states within and outside the pile wall throughout the pile installation process.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A GRIDAP-BASED IMPLEMENTATION OF TOPOLOGY OPTIMIZATION UNDER UNCERTAINTY FOR BRITTLE FRACTURE RESISTANCE

Maryam Maghazeh[1], Ayyappan Unnikrishna Pillai[2], Mohammad Masiur Rahaman[2] and Subhayan De[1]*

[1]Northern Arizona University
[2]Indian Institute of Technology Bhubaneswar

ABSTRACT

Topology Optimization is a practical and effective design tool for efficiently distributing material within a design domain to enhance structural performance as an objective. However, the fracture response of a structure can get altered by minor changes in the design. In addition, uncertainties in material properties, loading and boundary conditions can significantly affect the performance of the designed structure. In this study, an open-source Finite Element library in Julia called Gridap is used to develop a computationally efficient uncertainty-based topology optimization approach where the estimation of brittle fracture resistance in the design is facilitated through the application of a thermodynamically consistent phase-field method based on the virtual power principle. Furthermore, the effect of uncertainty is addressed during the design process by incorporating stochastic gradients based on a small number of realizations of uncertainty at each iteration, significantly reducing the computational cost for design under uncertainty. The effectiveness of this approach is demonstrated through benchmark examples in topology optimization.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATISTICAL INFERENCE WITH HIGH-DIMENSIONAL SURROGATE MODELS

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ABSTRACT

We propose a novel approach for propagating the model discrepancy from the measured quantities of interest (QoIs) to uncertainty quantification in the prediction of unmeasured QoIs. Such extrapolation situations occur when the predicted QoI is at a different location/time than the measurement of the same quantity, or when the predicted QoI is altogether different from the measured quantity. In the proposed approach, all the outputs of the system model are first mapped to an uncorrelated latent space, and surrogate models are constructed for the dominant principal features. Such mapping can readily handle high-dimensional output; in addition, for high-dimensional input, active subspace discovery is used to reduce the input dimension. Discrepancy terms are introduced in the latent space and estimated through Bayesian calibration using the measured quantities. The posterior distributions of the discrepancy terms (in the latent space) and the model parameters and observation errors (in the original space) are then propagated through the physics model to quantify the uncertainty in the prediction of the unmeasured QoIs. The formulation of discrepancy terms in the latent space offers a rigorous and efficient approach to propagate the model discrepancy information from measured to unmeasured QoIs, compared to existing approaches that either modify/augment the model parameter distributions or estimate the model form errors in the governing equations. The proposed approach is demonstrated for an additive manufacturing application, employing a heat transfer model for temperature distribution and a mechanical model for residual stress prediction in the manufactured part.

Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONVOLUTIONAL NEURAL NETWORK FOR IDENTIFYING EFFECTIVE SEISMIC FORCE AND RAPID RECONSTRUCTION OF SEISMIC MOTIONS IN BUILT ENVIRONMENTS AND SOILS

Shashwat Maharjan[1], Bruno Guidio[1] and Chanseok Jeong[1]*

[1]Central Michigan University

ABSTRACT

We present a Convolutional Neural Network (CNN) approach informed by data, utilizing sparse ground motion measurements to precisely characterize effective seismic forces within a truncated domain. Specifically, this paper introduces the prototype of a CNN capable of deducing Domain Reduction Method (DRM) forces, equivalent to incident waves, across all nodes in the DRM layer. This achievement is realized using sparse measurement data in a multi-dimensional setting, faced with incoherent incident waves. By using CNN-predicted effective seismic forces, simulation engineers can accurately reconstruct seismic wave responses in built environments and soils in a domain. This method empowers engineers to generate accurate assessments of the impact of earthquakes on both soils and critical structures. It enables the identification of vulnerable points or regions susceptible to potential damage and the planning of repair and maintenance. While the earthquake engineering community acknowledges the importance of this task, the application of an Artificial Neural Network (ANN) for DRM force identification and wave response reconstruction, particularly in multi-dimensional settings with incoherent waves, has remained unexplored by and large.

The methodology is applied to shear (SH) waves, of anti-plane motion, propagating into a domain truncated by a wave-absorbing boundary condition (WABC). Through effective CNN training using input-layer features (surface sensor measurements) and output-layer features (effective seismic forces at a DRM layer), substantial reductions in processing time are achieved compared to PDE-constrained optimization methods. Numerical experiments demonstrate the method's efficacy and robustness in identifying effective seismic forces, equivalent to incoherent incident waves, at a DRM layer.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CRYSTALLIZATION AND MICROSTRUCTURAL EVOLUTION INDUCED BY THERMAL DEFORMATION IN ADDITIVELY MANUFACTURED COCRFENI HIGH-ENTROPY ALLOY

Avik Mahata[1]*

[1]King's College

ABSTRACT

The field of additive manufacturing (AM) is rapidly progressing as it is driven by its unparalleled capability to fabricate components with intricate geometries and optimized functionalities. However, the nuanced influence of inherent material properties, such as crystal structure and compositional effects, on the nanoscale microstructural evolution in AM-fabricated metals remains largely unexplored, especially in the context of high entropy alloy (HEA). In this study, we leverage extensive molecular dynamics simulations and machine learning based image analysis to examine the rapid thermal deformation phenomena experienced by CoCrFeNi high-entropy alloy within the molten pool of AM processes. Our investigation seeks to uncover the fundamental physical principles governing crystal nucleation and growth amid the multifaceted thermal stresses characteristic of HEA in AM environments. Our findings reveal that the arcuate solid-liquid interface consistently advances toward the liquid domain until full crystallization is achieved, corroborating previously published experimental observations. Notably, the solidification kinetics adhere to a consistent pattern, transitioning from slow to rapid rates across different metals, attributed to the interplay between compressive thermal stresses and accelerated atomic dynamics. This high-entropy alloy exhibits rapid growth rates and robust columnar crystal formation. Moreover, the interplay between sharp thermal gradients and solute redistribution markedly influences the growth driving force, enhancing constitutional supercooling at the solidification front and impeding the advancement of columnar crystals. This phenomenon is especially pronounced in the CoCrFeNi alloy, as evidenced by the prominent amorphous phases and distinct nucleation sites observed in the upper regions of the melt pool. This investigation provides a comprehensive atomic-level understanding of the nucleation and growth mechanisms in AM-fabricated high-entropy alloys, offering valuable insights for the development of advanced materials with tailored microstructures and properties.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF AN ARTIFICIAL NEURAL NETWORK MODEL FOR PREDICTING DAMAGE OF SHIELDED LUNAR HABITATS

Arsalan Majlesi[1], Amir Behjat[2], Adnan Shahriar[1], David Avila[1] and Arturo Montoya[1]*

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[2]Purdue University

ABSTRACT

Micrometeorites consistently collide with the lunar surface at extremely high speeds, necessitating future lunar habitat structures to possess the structural integrity to endure these impacts. Among the materials under consideration for shielding lunar structures from micrometeorite impacts are regolith and aluminum. Finite Element (FE) dynamic explicit analysis proves to be a reliable method for evaluating the potential damage caused by micrometeorite impacts on these materials, thereby reducing the reliance on intricate and expensive high-velocity impact tests. However, these numerical analyses come with a high computational cost and demand expertise from users. Hence, this study involves training machine learning tools using a representative set of FE models to enable parametric analyses that effectively guide the analysis and design of space habitats. The predictions of perforation depth from the FE models were validated by comparing them against experimental test results available in the literature. The FE models were executed for a broad range of micrometeorite diameters and velocities, reaching up to 70 km/s. These outcomes were then utilized to train an Artificial Neural Network (ANN) model capable of predicting perforation depths on shielding panels based on material, micrometeorite diameter, and velocity. The ANN model demonstrated accurate predictions of perforation depths on potential lunar habitat designs, surpassing the performance of other predictive models like Decision Tree (DT) and Multiple Linear Regression (MLR). This study establishes a framework for the development of ANNs that contribute to the design of lunar habitats resilient to micrometeorite impacts.

POROMECHANICAL BEHAVIOR OF UNSATURATED SHALES

Roman Makhnenko[1] and Hyunbin Kim[1]*

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ABSTRACT

The development of subsurface engineering applications, such as shale gas and oil extraction, geological storage of hydrogen and carbon dioxide, and nuclear waste disposal, has increased interest in the hydro-mechanical behavior of shale-like geomaterials. When subjected to mechanical and thermal stresses, as well as the hydraulic pressures during both drainage and imbibition episodes, shaly sealing formations can trap pore fluids due to capillary pressure and changes in rock porosity. The water retention-induced mechanisms play a crucial role in the behavior of an unsaturated porous medium, but measuring unsaturated poroelastic parameters in the laboratory is challenging for materials where solid, pore, and fluid compressibility cannot be neglected. Biot poroelasticity theory has recently been extended from fully saturated to unsaturated states, allowing the calculation of macroscale constants using the microscale measurable properties under the saturated state and water retention curve. This enables the evaluation of bulk material constants at a given saturation without the need for time-consuming experiments that can take a few months for low-permeable shales. In this study, the unsaturated poroelastic parameters are measured for Opalinus Clay (shale), Maquoketa Shale, and Eau Claire Shale at the degrees of water saturation between 0.6 and 1. During the tests, the applied differential pressure between wetting and nonwetting fluid is on the order of a few MPa to exceed the capillary entry pressure and desaturate the specimen. The experiments under the undrained condition show that the unsaturated shales exhibit lower bulk moduli comparing to the saturated counterparts, mainly due to the changes in pore fluid compressibility. In addition, the drained compression tests reveal that the dry specimens are stiffer than the saturated ones since the presence of pore fluid can reduce the effective mean stress. The measured parameters are compared with the model predictions based on knowledge of water retention curve obtained from the porosimetry and capillary properties analyses. Some agreement between the theory and the measured undrained response of shales is observed, but it is noticed that the osmotic suction also plays an important role in the behavior of sodium-ion-enriched shales (e.g., Opalinus Clay). The modifications of the unsaturated poroelastic model in terms of the effective stress concept and osmotic suction are suggested in order to resolve the aforementioned issues and improve the predictability of the model for poroelastic behavior of shales at the degrees of water saturation above 0.6.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

QUANTIFICATION OF URBAN AND COMMUNITY RESILIENCE TO NATURAL HAZARDS

George Chatzikyriakidis[1], Gholamreza Moghimi[1], Nicos Makris[1] and Tue Vu[1]*

[1]Southern Methodist University

ABSTRACT

In view that cities will continue to house the majority of the world's population at an increasing rate in association with the face of climate change, this paper studies urban resilience by examining the response history of the mean-square displacement of the citizens of large cities prior and upon historic natural hazards strike. The recorded mean-square displacements of large numbers of cell-phone users from the cities of Houston, Miami and Jacksonville when struck by hurricanes Harvey 2017, Irma 2017 and Dorian 2019 together with the recorded mean-square displacements of the citizens of Dallas, and Houston when experienced the 2021 North American winter storm, suggest that large cities when struck by natural hazards are inherently and invariably resilient. The recorded mean-square displacements presented in this study also validate a mechanical model for cities, previously developed by the authors, which is rooted in Langevin dynamics and predicts, that following a natural hazard, large cities revert immediately to their initial steady-state behavior and resume their normal, pre-event activities. The same analysis framework is being used for the quantification of community resilience.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE PRESSURIZED SAND-DAMPER: A LOW-COST, LONG-STROKE, RATE/TEMPERATURE INDEPENDENT ENERGY DISSIPATION DEVICE

Nicos Makris[1] and Konstantinos Kalfas[2]*

[1]Southern Methodist University
[2]University of Texas at Tyler

ABSTRACT

This paper summarizes results from component testing on various configurations of a recently developed pressurized sand-damper in which a steel sphere is moving within a cylindrical tube filled with sand that is under pressure. The experimental campaign investigates the effects of the key design parameters of the damper, namely the effect of the clearance between the moving sphere and the cylindrical tube and the effect of the overall length of the damper to its force output. The recorded force-displacement loops when normalized to the strength of the pressurized sand-damper reveal remarkable order with stable behaviour and confirm decisively that the force output is rate-independent. The paper also presents recorded force-displacement loops where the sphere mounted on the piston-rod is replaced with a bolt where only the bolt-head and nut are protruding from the moving piston-rod. With this configuration, the pinching behaviour of the pressurized sand-damper at longer strokes is suppressed without generating large forces at longer strokes.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEISMIC RESPONSE OF SLENDER STRUCTURES EQUIPPED WITH INERTIAL DEVICES.

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[1]*Imperial College London*

ABSTRACT

This paper presents the results of numerical and experimental study on models of slender buildings equipped with inerto-viscoelastic devices subjected to support motion simulating a set of hazard-consistent seismic ground-motions. It describes models used as analogues of slender and tall buildings and outlines the protocol created to construct empirical displacement hazard curves. The models are equipped with a range of inertial devices whose influence and effectiveness in seismic response reduction is evaluated via hazard-consistent peak displacement hazard curves constructed from the experimental results. Tuned Viscous Mass Damper (TVMD), Tuned Mass Damper Ineter (TMDI), Tuned Inerter Damper (TID) and Tandem Tuned Mass Damper Inerter (TTMDI) configurations are studied. The results of this study show the relative advantages of TTMDI configurations over a wider spectral range and highlight the potential of inertial devices for passive seismic control. Comparisons are made with analytical solutions and the relative differences are identified and discussed. This paper constitutes the first attempt to evaluate the response of a variety of inerto-viscoleastic devices within a consistent hazard-consistent framework.

Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC WILDFIRE RISK ASSESSMENT AND RETROFITTING OPTIMIZATION FOR HILLSIDE TRANSPORTATION NETWORKS IN CALIFORNIA

Sven Malama[1], Debasish Jana[1], Fernando Szasdi-Bardales[2], Riyaaz Shaik[1], Sriram Narasimhan[1], Negar Elhami-Khorasani[2] and Ertugrul Taciroglu[1]*

[1]University of California, Los Angeles
[2]University at Buffalo

ABSTRACT

California's landscape is dotted with extensive high-fire severity zones, amplifying the risk of devastating wildfires. In hilly regions, the threat is further compounded, as evacuation options are predominantly downhill, posing significant challenges in the event of a wildfire. The limited space in these hillside environments often results in roads that are not inherently fire-safe, potentially leading to road closures or congestion during evacuation scenarios.

This study addresses the critical need for a comprehensive and proactive approach to wildfire risk assessment and retrofitting optimization for road networks in fire-prone areas. Focusing on wildland and wildland-urban interface (WUI) scenarios, our research makes use of a probabilistic framework that considers various fire outbreak scenarios. The objective is to propose retrofitting policies that enhance the resilience of transportation networks in the face of wildfire hazards.

The proposed retrofitting strategies are based on three key steps: (1) estimating wildfire occurrences and modeling fire growth, (2) conducting vulnerability assessments at both component (i.e., roadway) and system levels (i.e., transportation network), and (3) determining optimal retrofitting solutions within a specified budget. This study integrates the FARSITE fire propagation model for wildlands and the SWUIFT [1] model for WUI in areas identified through fuel maps. Graph algorithms and traffic assignments are then introduced to assess network-level vulnerability across various fire propagation scenarios. Subsequently, a heuristic optimization algorithm is employed to identify the most effective retrofitting measures, specifically focusing on evacuation availability of roads as well as on firebreaks and vegetation management. The framework incorporates essential socio-economic data, such as household income and the number of vehicles per household, to ensure that mitigation measures are both equitable and efficient.

The research focuses on the Los Angeles Hillside transportation network, an area characterized by both high fire severity and a network of narrow roads. This choice of location allows the framework to be tested and validated in a real-world scenario, offering practical insights into the challenges and opportunities associated with retrofitting in fire-prone hillside environments. The holistic and adaptive solution from the proposed framework demonstrates high potential in enhancing the resilience of transportation infrastructure in the face of escalating wildfire threats.

[1] Masoudvaziri, N., Bardales, F.S., Keskin, O.K., Sarreshtehdari, A., Sun, K. and Elhami-Khorasani, N., 2021. Streamlined wildland-urban interface fire tracing (SWUIFT): modeling wildfire spread in communities. Environmental Modelling & Software, 143, p.105097.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL INVESTIGATION OF THE CONICAL DOMES OF ARMENIA'S HISTORIC CHURCHES

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ABSTRACT

As the first nation to adopt Christianity in the early 4th century, Armenia has long held churches as a core component of its cultural identity. The earliest still-standing churches in Armenia date back to the 5th and 6th centuries. Key architectural details and construction techniques define the distinctive Armenian church style and form throughout their historical evolution. The most readily recognizable of these unique forms is the conical church dome. Rising tall above the general massing, built of local tuff masonry, these conical domes help define the lasting legacy of Armenian churches. The aim of this research is to conduct a holistic structural analysis of the conical dome typology in Armenian churches in order to 1) understand the behavior of these unique domed systems; 2) investigate common threats to their structural condition; 3) provide recommendations for prolonged structural health; and 4) offer a framework for feasible structural reconstructions of these domes on existing ruins. The domes will be analyzed by identifying geometrical properties, performing finite element analysis, and assessing local tuff material properties and rubble masonry construction techniques. Current findings represent preliminary results in a thorough, future on-site investigation of this Armenian church dome typology.

Advances in vibration and structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FLOOR VIBRATION IN MASS TIMBER OFFICE BUILDINGS

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ABSTRACT

Even though mass timber construction is becoming more common, not many footfall vibration tests have been performed on timber composite floors. Most tests involve only one bay without the effects of continuity from adjacent bays, and they were often conducted in a simplified lab setting, which does not mimic the complexity of real buildings with partitions, MEP system and furniture. The concern over vibrations in mass timber floors underscores the need for conducting further in-situ testing and analysis. This presentation delineates a comprehensive experimental-numerical campaign conducted within a recently built mass timber office building in California. The focus is specifically directed towards examining the floor's response to footfall forces. The walker-induced amplitudes at various pace rates are compared against two finite element models in ETABS. The tested floors demonstrate compliance with vibration requirements in an office environment across selected locations.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPERATIONAL HEALTH MONITORING OF BRIDGES USING MULTIMODAL DATA FUSION AND BAYESIAN FINITE ELEMENT MODEL UPDATING TECHNIQUES

Niloofar Malekghaini[1], Hamed Ebrahimian[1], Farid Ghahari[2], Mathew Bowers[3], Ertugrul Taciroglu[2] and Frederick Harris[1]*

[1]University of Nevada, Reno
[2]University of California, Los Angeles
[3]SC Solutions

ABSTRACT

This study introduces an innovative approach for operational health monitoring and damage diagnosis of aging bridges through integrating multi-modal data within a finite element model updating framework. In this approach, the data related to the bridge traffic is collected using regular traffic cameras, while the bridge's vibrational responses are collected using wireless accelerometer networks. This multimodal data is fused together and integrated with mechanics-based models of bridges through a Bayesian inference and model updating technique. During the model updating process the bridge model parameters are estimated, the location and extent of damage are inferred, and the dynamic load of vehicles traversing on the bridge are determined. One of the key features of this approach is the incorporation of deep learning and computer vision techniques to enhance the automation and efficiency of data processing in the procedure of operational health monitoring. Multi-camera and multi-object tracking models are used to detect and track the footprint of the tires of vehicles traversing on the bridge. The location of contact point of tires on the bridge deck, along with the collected vibrational responses, serves as input for the Bayesian finite element model updating framework. Upon successful verification of the theoretical formulations, the proposed method is validated using data collected from actual bridges. In this presentation, technical details of the approach along with the outcomes of validation studies will be presented.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SURFACE AND SUBSURFACE DAMAGE DETECTION IN CONCRETE STRUCTURES USING RGB AND IR IMAGERY

Lokeswari Malepati[1], Nikesh Thammishetti[1] and Suriya Prakash S[1]*

[1]Indian Institute of Technology Hyderabad

ABSTRACT

Recent advancements in image-based damage detection involves integrating multiple modalities to harness complementary information. Thus, increasing the robustness of deep learning models used for the structural health monitoring. One such case of integrating information from multiple sources is the fusion of infrared (IR) and RGB images. Recent findings [1] have showcased the benefits of combining features from IR and RGB, especially in challenging lightning conditions. Additionally, ability to detect subsurface defects is another distinctive advantage of using IR images. This investigation focuses on evaluating the usage of RGB and IR imagery for surface and subsurface damage segmentation. To facilitate the development of a robust model, a dataset of RGB and IR pairs featuring different combinations of cracks, spalling, exposed rebar, and delamination was curated. The curated images go through the crucial step of image registration and followed by the annotation of the images. Here, we propose an algorithm that makes use of Speeded-Up Robust Features (SURF) detector and the Mutual Information (MI) similarity criterion [2]. The proposed methodology demonstrates effectiveness even in the cases with low similarity between the IR and RGB modalities. For training the model, we employ the early fusion strategy, integrating the information at pixel level of raw IR and RGB images. Further, a comparative analysis, evaluating the performance of transformer-based architecture against the CNN based deep learning model is carried out.

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Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-DIRECTIONAL RTHS OF A 3 STORY MRF WITH NONLINEAR VISCOUS DAMPERS AND SOIL-STRUCTURE INTERACTION USING NEURAL NETWORKS

Faisal Nissar Malik[1], Davide Noè Gorini[2], James Ricles[1], Safwan Al-Subaihawi[1] and Thomas Marullo[1]*

[1]Lehigh University
[2]Sapienza Università di Roma

ABSTRACT

Nonlinear dynamic analysis is a valuable tool that enables the evaluation of structural response under a variety of natural and man-made hazards. However, this approach is only applicable to structures where accurate numerical models of the structural system are available. Real-time hybrid simulation (RTHS) is a technique that enables the researchers to assess the structural response where accurate analytical models are not available and show a complex rate-dependent behavior. RTHS involves numerically modelling the analytical substructure while the complex elements are modeled physically, solving the resulting equations of motion in real-time to determine the structural response of the system. A major challenge in RTHS is to account for the effects of soil structure interaction. Soil structure interaction can have a substantial effect on the response of a structural system, especially the efficacy of response modification devices. Therefore, accounting for this interaction is crucial when assessing the performance of a structural system under natural hazards. However, modeling soil-structure interaction in a RTHS is complex due to the large size of the soil domain, making experimental modeling impractical. Numerical modeling of the soil domain is also challenging using the conventional finite element method due to the large number of elements and degrees of freedom involved, making a RTHS computationally expensive. To address these limitations, the present study focuses on multi-directional RTHS for complex systems under seismic hazards, incorporating soil-structure interaction effects through neural networks. A three-story steel building with moment resisting and damped braced frames is modelled numerically and the nonlinear viscous dampers are modelled experimentally. Effects of soil-structure interaction are incorporated into the RTHS by modelling the soil domain using neural networks, which enables the computations to be done in real-time and therefore making RTHS possible. The neural network is developed and trained in Python and the Python-based neural-network and Simulink-based numerical model of the analytical substructure are connected using SCRAMNet to ensure low-latency communication. In summary, this innovative approach not only expands the applicability of RTHS to structures lacking precise analytical models but also addresses the challenge of incorporating soil-structure interaction using neural networks into a RTHS. This paves the way for real-time simulations and comprehensive hazard assessments in structural engineering. The presentation will include an overview of the approach that includes the neural network model and machine learning details, in addition to the architecture for the RTHS and results from the RTHS of the subject building.

Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A CURRENT MAPPING OF THE PERMEABLE BOUNDARY BETWEEN DESIGN, INNOVATION, AND ACADEMIC RESEARCH

Elisabeth Malsch[1]*

[1]Thornton Tomasetti

ABSTRACT

As a forensic engineer and active participant in industrial research and development efforts, I have the opportunity to see and push the boundary of what is well established and reliable within the field of engineering mechanics and where the vast unknowns of our field are still waiting to be answered. As a forensic engineer I get to see what did not work what the limits of our assumptions, our collective ability to communicate, and our tools is. In industrial research and development efforts I have the opportunity to interact with world class researchers and academic institutions.

One topic of interest to EMI may be the increasing collection of data and instrumentation of the physical world around us. This collection of information allows all of us in engineering mechanics have the opportunity to experiment with real life structures and systems. And in doing so I am sure that we will continue to push the boundary of what we can design so that it is more reliable more efficient and more purpose driven and addresses the evolving challenges of our time.

Examples of problems on the boundary of our current understanding include: the behavior of nonlinear components and how slip and cracking contribute to ductility and robustness - an example is the failure of the socket of the Arecibo telescope; fracture and fatigue in thick steel sections that are increasingly more orthotropic than isotropic; broadening our design criteria to include the risks from the new energy economy like lithium ion batteries; and new kinds of construction like timber.

The specific topics focused on in the 15 minute presentation will be coordinated with the other presenters.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL METHOD TO EVALUATE THE FRACTURE BEHAVIOR OF THE SHOTCRETE-CONCRETE INTERFACE

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ABSTRACT

Shotcrete is a popular overlay material used in concrete repairs, especially in overhead and vertical construction where traditional formwork is challenging to install, time-consuming, and expensive. However, this practice could also reduce the longevity of structures if the interface bond properties between shotcrete and existing concrete are not well developed. Present evaluation methodologies predominantly hinge on characterizing shotcrete-concrete interface bonds based on tensile strength despite the prevalence of dominant shear-type loads in the interface region. Moreover, the effect of inherent flaws, such as microcracks, which could result in premature failure, is not considered in strength-based tests. Consequently, there exists a demand for innovative testing methods that specifically assess the influence of preexisting flaws on the shear behavior of the shotcrete-concrete interface bond.

This talk will primarily focus on introducing a novel Mode II fracture test for cementitious bi-material interface bonds. It will also include a discussion about understanding the effect of shear-type loading on the failure patterns and freeze-thaw durability of the shotcrete-concrete interface. The potential of the proposed test in characterizing shotcrete repairs and substrate surface texture is also explored by comparing different surface preparation techniques: chipped (C), pressure-washed (PW), sandblasted (SB), and as-cast (AC).

The results indicated that the proposed test is sensitive to the substrate surface preparation technique and can be used as an initial screening test in concrete repairs. The test also captured the variation of substrate surface texture after subjecting the specimens to cyclic freeze-thaw weathering. Additionally, the talk will focus on a cohesive zone model for simulating the shotcrete-concrete interface bond. The results indicate that both the interface cohesive strength and the critical interface bond fracture energy govern the failure modes of the hybrid cementitious composite system, emphasizing the importance of evaluating the substrate-to-overlay interface bonds based on fracture-based tests simultaneously with the strength-based tests. These parameters could be improved using mechanical methods such as substrate surface preparation before applying the overlay. The proposed test could be used in complement with strength-based tests as a quality control tool for concrete repairs.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REPAIRABLE CONCENTRIC BRACED FRAMES THROUGH ADDITIVE MANUFACTURING

Islam Mantawy[1] and Hamdy Farhoud[1]*

[1]Rowan University

ABSTRACT

The use of special concentrically braced frames (SCBFs) in lateral load-resisting systems has increased in the last decades. SCBFs, according to the latest AISC provisions, are designed to provide significant inelastic deformation capacity primarily through tensile yielding and post-buckling inelastic deformation which is suitable for seismic regions. Even though SCBFs satisfy design requirements for life safety, they sustain high levels of damage primarily buckling which results in economic losses due to the need for replacement. The design and analysis of SCBFs require careful consideration of several factors, including the properties of the materials used, the geometry of the brace and structure, and the expected seismic forces. One advancement in bracing systems is the development of buckling restrained braces which restrict bucking by encasing the steel member with stiff materials (commonly concrete) during the seismic loading. The seismic resisting systems are the weakest systems that counteract earthquakes. However, some elements (connections, beams, columns, etc.) of the system should be seismically protected (remain elastic). Recent research efforts try to propose weak links to concentrate damage in specific locations within the system. These links may take the form of yielding components, friction/viscous dampers, or fuses; aiming to enhance the overall seismic resilience of the structure.

The new concept proposed in this presentation focuses on dividing the brace into three segments and concentrating the damage due to tensile yielding and inelastic buckling in the middle segment of the brace (fuse) while protecting the rest of the bracing member allowing owners to replace/repair the damaged portion (fuse) after high-level seismic excitation. The replaceable fuses, recycled from the damaged fuse, are additively manufactured to achieve desired ductility through optimized geometry. It should have the same level of tension, compression, and energy dissipation as conventional bracing. The presentation will include a description of numerical and experimental results from a small-scale specimen/fuse tested under different loading protocols as well as a numerical test case for a chevron bracing system under cyclic protocol load at Rowan University’s Additive and Robotic Construction Laboratory (ARC-Lab).

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SUSTAINABLE INFRASTRUCTURE THROUGH TOPOLOGY-OPTIMIZATION-BASED ADDITIVE CONSTRUCTION

Islam Mantawy[1], Jenna Migliorino[1], Anthony Mackin[1], Aly Ahmed[1] and Zaid Hanoun[1]*

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ABSTRACT

For decades, concrete structures have been constructed using cementitious materials through conventional methods using formworks (either cast-in-place or precast). Concrete with a sufficient slump is needed to fill up the formwork. This approach results in significant material wastage (where the material is placed in areas with low to very low stresses) and increases the carbon footprint of structures. Additive construction provides unique opportunities to build form-free structural elements with complex geometry, enabling topology and structural optimization.

Topology optimization is a shape optimization method that uses algorithmic models to optimize material layout within a user-defined space for a given set of loads, conditions, and constraints. Topology optimization maximizes the performance and efficiency of the design by removing redundant material from areas that do not need to carry significant loads to reduce weight or solve design challenges like reducing resonance or thermal stress. Topology optimization seeks to magnify the performance of the design while also minimizing the amount of material used.

This presentation includes 1) the development of 3D-printed versions of concrete with lower embodied carbon; 2) utilization of advanced modeling techniques for topology and structural optimization of structural elements; 3) utilization of strut-and-tie methods for topology and structural optimization, and 4) small scale and large scale additive construction for optimized structural beams. The presentation will conclude with a detailed comparison between conventionally constructed beams and additively constructed beams in terms of materials saving and emission reduction.

IS ADDITIVE CONSTRUCTION READY FOR SEISMIC REGIONS? – A NEW SEISMIC PROTECTIVE SYSTEM ENABLED BY ADDITIVE CONSTRUCTION

Islam Mantawy[1], Anthony Mackin[1], Jenna Migliorino[1] and Hamdy Farhoud[1]*

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ABSTRACT

Conventional design for bridges in seismic-prone areas relies on ductility concept by concentrating the damage at plastic hinges at the ends of the columns. Even though constructing bridges with this design concept is adequate for life safety, the bridge columns exhibit significant damage and residual deformations resulting in expensive repairs or the need for full replacement. Over the last decades, researchers developed several seismic protective systems to minimize the damage and enable repair after strong earthquakes. Systems include rocking systems, dampers, and seismic isolation systems.

New novel ideas emerged to adopt new concepts such as “rocking columns” with accelerated bridge construction techniques to enhance construction quality, speed construction, and even enable repairs using external reinforcement or damping systems. The new innovative system proposed by the presenters integrates several seismic protective concepts to achieve self-repair and deconstruction through additive construction of the entire bent substructure. In this proposed system, protected elements such as bridge bent caps, columns, and footings are additively constructed. In addition, the columns are designed to rock at interfaces between the columns and bent cap/footing, and external elements are added to dissipate energy to enable self-repairing. The presentation will include a description of numerical and experimental results from a small-scale specimen tested under seismic excitations at Rowan University’s Additive and Robotic Construction Laboratory (ARC-Lab).

Advances in bridge health monitoring: Data-driven and machine learning methods, indirect monitoring, crowdsourced mobile sensing
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRAPH NEURAL NETWORKS BASED VIRTUAL SENSING: A MACHINE LEARNING APPROACH FOR FATIGUE ASSESSMENT

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ABSTRACT

Advancements in artificial intelligence are tightly linked to enhanced reliability and accuracy in virtual sensing area. Specifically, the development of new machine learning architectures notably drives enhancements in methodologies able to generate data from virtual sensors. The possibility to replace physical sensors with virtual ones mitigates network costs and overcomes the challenges associated with using physical sensors in difficult to access areas. This is particularly evident in fatigue assessment procedures, where the traditional reliance on recording strain data involves high equipment costs, laboriousness, and the necessity to collect data from critical structural points. Developing streamlined procedures for evaluating fatigue behavior holds significant importance in effectively managing steel bridges, which are prevalent across the United States and prone to fatigue-related issues. This study presents the use of graph neural networks to convert acceleration data into strain data to create virtual sensors in a fatigue assessment perspective. This emerging network architecture exploits physics information to support this task, displaying promising results through a numerical case study.

AUTOGENOUS SHRINKAGE AND SWELLING OF SUBMERGED OR SEALED SPECIMENS OF ULTRA-HIGH-PERFORMANCE CEMENT PASTE

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ABSTRACT

Ultra-high-performance concrete (UHPC) is prone to develop shrinkage cracking compared to conventional concrete. This is due to higher brittleness and high autogenous shrinkage superposed on drying shrinkage, which is caused by the low water-to-cement ratio. Understanding the shrinkage is fundamental for applying UHPC in the additive manufacturing field. The research aims to understand the fundamental difference in autogenous and drying shrinkage between the UHPC and conventional mortar systems with the help of 3D scanning techniques. A new technique is developed for autogenous shrinkage to measure the shrinkage or swelling with minimal mechanical constraints submerged in water or sealed conditions with self-desiccation (achieved by submergence in oil). This technique is developed to replace the test ASTM C1698 Autogenous Strain in a corrugated tube since, in this test, significant friction between the tube and the measuring cell constrains the specimen mechanically, suppressing the autogenous shrinkage to be measured. The technique consists of casting or printing UHPC specimens from which slices (or slabs) with a controlled thickness of 0.5 mm are cut after one day of curing. These specimens are placed in a Petri dish (attached with a small piece of carbon tape) and are submerged in water or paraffin oil. In water submergence, the self-desiccation is suppressed by water diffusion, which is sufficiently fast in a slab only 0.5 mm thick. Under oil, no water can be supplied, and so the self-desiccation and the resulting autogenous shrinkage proceed unhindered. The volumetric shrinkage and swelling are measured using the laser confocal microscope as a function of time. For comparison, a mini-ring test is developed to measure the drying shrinkage of ultra-high-performance concrete. This is a half-scaled-down restrained ring test, the conventional ring test, since UHPC has no coarse aggregates. The concrete is cast between a steel ring and a 3D-printed mold. The specimens are demolded, and the top surface is capped with epoxy to only permit radial moisture movement o. The samples are placed into an environmental chamber with 50% relative humidity. The crack initiation day, the crack width, and the specimen geometry are acquired daily by 3D scanning. Specimens with nanoclay added during casting are also studied to compare the behavior of plain UHPC with the nanomodified UHPC whose rheological properties suit the 3D printing system. The present experimental campaign will inform the computational modeling of 3D printable UHPC structures and lead to the proper consideration of shrinkage in material design.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING SYSTEM DIAGNOSTICS AND PERFORMANCE BY EMBEDDING HUMAN INTERACTION WITHIN DIGITAL TWINS

John Martins[1] and Katherine Flanigan[1]*

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ABSTRACT

Digital twins (DTs) have emerged in recent years to improve the performance of, and facilitate the detection, diagnosis, and correction of faults in, infrastructure systems. While this control paradigm is appropriate for traditional infrastructure systems (e.g., stormwater system operation), there are increasing dependencies between civil and mechanical infrastructure and the humans who use it. Humans stand to play many roles within DTs, such as within the plant, as input loads, as the controller, engaged in human-machine control symbiosis, and within multi-agent loops. Such DTs need to observe and control the interdependencies between humans and infrastructure to enhance the overall performance of either the social or physical systems. While sensors can be (and already ubiquitously are) densely installed within infrastructure to observe its behavior, the absence of quantitative measurement of the human's influence on the physical system limits the utility of the output-only data collected within DTs. There is a need to better quantify humans as inputs to a wider array of infrastructure systems in order to reap the full potential of emerging DTs. In this work, we augment traditional DT models by (1) embedding privacy-preserving computer vision to measure human behaviors interacting with infrastructure systems and (2) learning correlations between infrastructure health/performance and human interaction behaviors. While this advancement of DTs is relevant across diverse application areas (e.g., indoor occupant modeling, energy management), we focus on the case study of diagnosing human-induced root causes of advanced manufacturing (AM) faults and production inefficiencies due to the enormously rich and transient human-infrastructure interactions that occur in this space. The complexity of the interactions studied requires computing to be integrated within the framework at a variety of scales, which have yet to be well studied across civil and mechanical infrastructure systems. Specifically, the model spans four quadrants: physical twin-static, physical twin-transient, DT-static, and DT-transient, where the machine and the human are in the physical twin-static and physical twin-transient quadrants, respectively, with their interaction sitting at the interface. The machine and human systems are monitored directly (using machine data logs and computer vision from depth sensing, respectively) providing measurement outputs that conjoin the physical elements with the cyber elements of the model. Based on the coupling of the two systems, the human receives corrective actions in near real time. The human behavior and interaction measurements and machine data are synthesized in the digital realm to derive control inputs that feed back to the human.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF EXTRUDED THIN-WALLED BEAMS

Ameer Marzok[1] and Haim Waisman[1]*

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ABSTRACT

Thin-walled beams have many applications in various engineering disciplines. While these elements have slender cross-section that leads to a desired high stiffness-to-volume ratio, they are prone to global and local buckling. Therefore, buckling considerations are essential to ensure an adequate performance of these elements.

In this work, we present a new topology optimization framework for the design of thin-walled beams produced by extrusion. The latter manufacturing process leads to a uniform cross-section along the length beams. To this end, a novel extended/generalized finite element method (XFEM/GFEM) with global enrichment functions is used to analyze the displacements and buckling loads of these elements, alleviating the need for detailed 3D finite element models, even when complex deformation modes are involved.

Our objective is to minimize the weight of the beams while accounting for displacements, stress, and buckling constraints. We employ a density-based gradient-based topology optimization method where the critical buckling loads are computed via the eigenvalues of a linearized buckling problem. The gradients of the objective function and constraints are derived analytically using the adjoint variable method.

Several case studies that involve conceptual and practical problems of thin-walled beams will be presented illustrating the viability of our method.

Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCEMENTS IN STRUCTURAL SYSTEM IDENTIFICATION FOR FLOATING OFFSHORE WIND TURBINES: MODEL CALIBRATION

Martin Masanes Didyk[1], Yashar Eftekhar Azam[1], Ibrahim Taze[1] and Barbara Costa Girafa[1]*

[1]*University of New Hampshire*

ABSTRACT

This study marks a significant advancement in the field of structural system identification, particularly within the operational context of offshore floating wind turbine (FOWT) systems. The research addresses a crucial challenge in developing digital twins for FOWT and other operational civil infrastructure—precise modeling of the studied system. To overcome this challenge, we present an analytic model implemented in MATLAB for a 7-degree-of-freedom (DOF) FOWT. This model is meticulously calibrated to provide accurate estimations of the system states, taking into account added mass and added damping parameters. We explore various minimization algorithms and optimization functions, conducting a thorough cross-comparison of results. This proof-of-concept effort serves as a foundation for our future work, where the integration of information from the calibrated analytic model, real input, and output measurements will guide the development of a digital twin for a laboratory-scale model of a FOWT.

PHYSICS-CONSTRAINED DATA-DRIVEN VARIATIONAL METHOD FOR DISCREPANCY MODELING

Arif Masud[1] and Shoaib Goraya[1]*

[1]University of Illinois Urbana-Champaign

ABSTRACT

The effective inclusion of a-priori knowledge when embedding data in physics-based models of dynamical systems can ensure that the reconstructed model respects physical principles, while simultaneously improving the accuracy of the solution in the previously unseen regions of state space. This talk presents a physics-constrained data-driven discrepancy modeling method that variationally embeds measured data in the modeling framework. The hierarchical structure of the method yields fine scale variational equations that facilitate the derivation of residuals which are comprised of the first-principles theory and sensor-based measurements of the dynamical system. The embedding of the sensor data via residual terms leads to discrepancy-informed closure models, thereby resulting in a method which is driven not only by boundary and initial conditions, but also by measurements that are taken at only a few observation points in the target system. Specifically, the data-embedding term behaves like a residual-based least-squares loss function, thus retaining variational consistency. The structure of the loss function is analyzed in the context of variational correction to the modeled response wherein loss function penalizes the difference in the modeled response from the measured data that represents the local behavior of the system. Formulation is then extended for transient analysis and the effect of the variationally embedded loss function on time dependent response of the system is analyzed under a variety of loading conditions. Specifically, the damped solution and correct energy time histories are recovered by including known data in the undamped situation. The enhanced stability and accuracy of the DDV method is manifested via reconstructed displacement and velocity fields that yield time histories of strain and kinetic energies that match the target systems. The proposed DDV method also serves as a procedure for restoring the eigenvalues and eigenvectors of a deficient dynamical system when known data is taken into consideration. Method is applied to smooth as well as non-smooth model problems and mathematical attributes of the formulation are investigated.

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Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LEAST SQUARE FINITE ELEMENT MODEL FOR ANALYSIS OF MULTILAYERED COMPOSITE PLATES UNDER ARBITRARY BOUNDARY CONDITIONS

Christian Mathew[1] and Yao Fu[1]*

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ABSTRACT

Laminated composites are widely used in many engineering industries such as aircraft, spacecraft, boat hulls, racing car bodies, and storage tanks. We analyze the 3D deformations of a multilayered, linear elastic, anisotropic rectangular plate subjected to arbitrary boundary conditions on one edge and simply supported on other edge. The rectangular laminate consists of anisotropic and homogeneous laminae of arbitrary thicknesses. This study presents the elastic analysis of laminated composite plates subjected to sinusoidal mechanical loading under arbitrary boundary conditions. Least square finite element solutions for displacements and stresses are investigated using a mathematical model, called a state-space model, which allows us to simultaneously solve for these field variables in the composite structure's domain and ensure that continuity conditions are satisfied at layer interfaces. The governing equations are derived from this model using a numerical technique called the least-squares finite element method (LSFEM). These LSFEMs seek to minimize the squares of the governing equations and the associated side conditions residuals over the computational domain. The model is comprised of layerwise variables such as displacements, out-of-plane stresses, and in-plane strains, treated as independent variables. Numerical results are presented to demonstrate the response of the laminated composite plates under various arbitrary boundary conditions using LSFEM and compared with the 3D elasticity solution available in the literature.
Keywords: Multilayered composite and sandwich plate, Transverse stress, Continuity condition, Arbitrary boundary condition, Layerwise theory, Least-squares formulation

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EIGENVALUE PROBLEMS IN STOCHASTIC MECHANICS: A QUANTUM COMPUTING SOLUTION TREATMENT

Ilias Mavromatis[1] and Ioannis Kougioumtzoglou*[1]

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ABSTRACT

A quantum computing approach is developed for solving eigenvalue problems of relevance to stochastic mechanics applications, such as modal response analysis of structural systems. The motivation relates to the fact that the computational complexity of the numerical solution of a deterministic eigenvalue problem, using a classical computer, is of the order of O(n^3), where n is the dimension of the considered matrix [1]. Clearly, if the eigenvalue problem is random originating, for instance, from a stochastic finite element formulation of the governing equations of motion, the computational cost increases further. Indeed, considering a standard Monte Carlo simulation (MCS) solution treatment, the cost becomes of the order of O(N*n^3), where N is the number of realizations in the MCS scheme. Obviously, the cost becomes prohibitive for large-scale finite element models of complex structural systems [2]. To address this challenge, the potential of quantum computers for performing complex tasks vastly more efficiently than classical computers is explored herein. Specifically, a variational quantum algorithm is proposed based on the original work in [3] for treating eigenvalue problems of interest in engineering mechanics. The performance of the algorithm, in terms of accuracy and efficiency, is assessed in conjunction with various numerical examples.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A REDUCED-ORDER FORMULATION OF THE WIENER PATH INTEGRAL TECHNIQUE FOR EFFICIENT STOCHASTIC RESPONSE DETERMINATION OF NONLINEAR SYSTEMS WITH SINGULAR DIFFUSION MATRICES

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ABSTRACT

The Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear dynamical systems relates to treating the system response joint transition probability density function (PDF) as a functional integral over the space of all possible paths connecting the initial and the final states of the response vector [1]. Further, the functional integral is evaluated, ordinarily, by resorting to an approximate approach that considers the contribution only of the most probable path. This corresponds to an extremum of the functional integrand and is determined by solving a functional minimization problem that takes the form of a deterministic boundary value problem. Recently, to increase the computational efficiency associated with the WPI technique, a reduced-order WPI variational formulation was developed in [2]. This reduced-order formulation can be construed as an efficient dimension reduction approach that renders the associated computational cost independent of the total number of stochastic dimensions of the problem. Concisely stated, the technique can determine directly any lower-dimensional joint response PDF corresponding to a subset only of the response vector components by utilizing an appropriate combination of fixed and free boundary conditions. In this paper, the reduced-order formulation of the WPI technique is extended to account also for constrained variational problems originating from systems exhibiting singular diffusion matrices [3]. Indicative examples include systems with only a subset of their degrees-of-freedom excited, hysteresis modeling via auxiliary state equations, and energy harvesters with coupled electro-mechanical equations.

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Objective resilience: Multi-scale resilience measures for electric power networks in climatic hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RISK ASSESSMENT AND RELIABILITY MODELING OF TRANSMISSION LINE SYSTEMS UNDER SEVERE WEATHER CONDITIONS

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ABSTRACT

Vulnerability of transmission line systems to cascading failures during severe weather such as hurricanes, tornadoes, and other extreme wind events has resulted in extensive and widespread outages in prior incidents within the United States. Developing a reliability model, along with an examination of consequence of such failures, will provide valuable insights into the system-level risks associated with transmission lines. This risk representation serves as a valuable instrument for evaluating the vulnerability of each system to failures and underscores the identification of critical parameters capable of mitigating the risk of a complete system failure. This article presents a reliability model, conducts a consequence analysis for the transmission tower system, and offers a risk assessment for a transmission line system. Limit states are identified by looking into the event that transmission line cascades by either of cable rupture, leg member buckling, and tip displacement exceedance of towers. Uncertainties of material, cable diameter, cable length, and cable sag are considered for the model. The research explores wind hazard, integrating a wind-load model that incorporates coherence in both horizontal and vertical dimensions. It accounts for uncertainties in wind speed, direction, gust factor as random variables. The analysis utilizes realistic drag coefficients based on wind-tunnel tests conducted for the tower system in the case study. Monte Carlo sampling for precise probabilistic assessment is used. A thorough risk profile of the entire system is produced by calculating the total expected system cost along with the probability of failure.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE MODELING OF LOCALIZED DAMAGE IN CERAMIC MATRIX COMPOSITE STRUCTURES WITH THE GENERALIZED FINITE ELEMENT METHOD

Bryce Mazurowski[1], Patrick O'Hara[2] and Armando Duarte[1]*

[1]University of Illinois Urbana-Champaign
[2]Air Force Research Laboratory

ABSTRACT

Ceramic Matrix Composites are showing promise as a structural material in high-speed aircraft. These materials have excellent strength-to-weight ratios and are resilient in the extreme environments encountered with high-speed structures. High-speed structures have complicated loading and structural features that shrink the structural length scale. CMCs bring several relevant length scales considerably larger than traditional metals, especially when modeling material failure. As the structural and material length scales approach each other, fundamental assumptions of homogenization theory are no longer valid. This requires a more rigorous, and significantly more expensive, analysis of the structure. However, this convergence of length scales typically occurs in localized areas of the structure: around sharp loads, high-gradient temperature profiles, connections, material interfaces, etc. A multiscale method based on the Generalized Finite Element Method with global-local enrichment functions (GFEMgl) is used to incorporate the local structural features, relevant material microstructure, and nonlinear constitutive behavior at these hot spots into global structural behavior on the fly. The proposed method can use homogenized material models throughout the majority of the structure, where there is sufficient separation of length scales. A damage model formulated to capture CMC failure modes at an intraply level is used to capture the nucleation and progression of damage in structural hot spots where homogenization theory is not valid. The method is shown to capture damage nucleation and progression accurately and efficiently in CMC structures when compared to industry-standard methods.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASYMPTOTIC THEORY FOR THIN SECOND-GRADIENT ELASTIC PLATES

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ABSTRACT

We derive the leading order energy and equilibrium equations for a thin plate comprised of a second-gradient elastic material. We utilize a dimension reduction procedure that yields a plate model valid to first order in the plate thickness. The novelty of our model, furnished by the second-gradient effect, is that the first order leading energy includes both membrane and bending effects and thus provides a well-posed system that is conducive to existence and uniqueness studies for energy minimizers. This contrasts with conventional theories of plates and shells, which when derived from first-gradient continua, require third order terms in the plate thickness to regularize the problem. This report is motivated by recent research thrusts into higher-gradient continua which have unveiled their ability to replicate unconventional material behavior in conjunction with the apparent lacuna in the contemporary theory regarding rigorous models for rods, plates, and shells comprised of these nonstandard materials.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL ASSESSMENT OF 19TH CENTURY WOOD TRUSSES: A CASE STUDY OF THE BROOKLYN FRIENDS MEETING HOUSE ROOF

*Melanie McCloy**[1]

[1]*Old Structures Engineering*

ABSTRACT

Throughout the 19th century, engineers in the United States relied on trusses to span rivers and raise roofs above heads. These trusses were primarily designed with empirical methods and without formal analysis until Squire Whipple published A Work on Bridge Building in 1847, describing how to properly analyze and design a truss for the first time (Whipple 1847; Gasparini and Provost 1989). As a result, trusses designed in the early-to-mid 19th century can be irrational and inefficient compared to trusses designed just 10-15 years later. By looking at a case study of a mid-19th century truss roof, we can see that such truss structures may not behave as the builders intended and are structurally inadequate under modern load requirements. We need to understand and upgrade inadequate heritage structures to ensure the safety of current users and allow for any future changes in use.

This presentation examines the wood roof trusses of the Friends Meeting House in Brooklyn, NY, built in 1857. It will place the construction within the larger context of truss development, assess the structural condition of the roof trusses, and analyze the roof trusses using both historic and modern methods to understand its structural behavior. Finally, the presentation will propose a reinforcement method to improve the structural performance of the roof under current required loads and discuss the feasibility of installing solar panels on the roof of the meeting house. Studying the performance of the structure over time demonstrates the importance of learning from the past to understand the present and adapt for the future.

Citations:

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Innovations and advances in passive, active, and semi-active structural control

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMBATING HARDENING BEHAVIOR IN SHALLOW TUNED SLOSHING DAMPERS

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ABSTRACT

Historically, using a supplementary damping system to control the wind-induced motion of tall buildings was often an afterthought used to solve problems identified during the design process. Recently, many structures are being planned around the use of a tuned mass damper (TMD) or tuned sloshing damper (TSD) to enable them to reach new heights above very slender building footprints. TSDs, which consist of a large partially filled tank of water containing internal obstructions (screens, paddles, baffles), are often the most economical system for these applications.

A fundamental consideration for TSD performance is ensuring proper tuning to the primary structure. The natural frequency of a TSD is a function of its length and water depth. To maintain a reasonable tank length when tuning a TSD to a long-period structure, the water depth must be shallow. Sloshing in shallow water TSDs is highly nonlinear, which can cause the excitation of many higher order modes of sloshing. Nonlinear coupling among the different sloshing modes leads to a hardening-spring type behavior. If the hardening in a shallow TSD is significant, the damper will become de-tuned from the primary structure, which severely reduces its performance. As a result of this performance degradation, implementing shallow TSDs is not always feasible for long-period structures.

Combating hardening in shallow TSDs without compromising the fundamental sloshing mode performance will help to improve their effectiveness and applicability to long-period structures. This study investigates a method of de-coupling the sloshing modes by installing a flat horizontal baffle across the middle of the TSD. The purpose of this plate is to alter the mode shapes and frequencies of higher order sloshing modes, thereby reducing the coupling between the modes, while leaving the fundamental sloshing mode unaffected.

In this study, the performance of a shallow TSD with and without a horizontal baffle plate is evaluated through experimental shake table testing and numerical modeling. The results indicate that the horizontal baffle plate effectively reduces the hardening behavior of the shallow TSD while maintaining the performance of the fundamental sloshing mode.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SHAPE-BASED COMPUTATIONAL APPROACH FOR IN VIVO CARDIAC TISSUE PROPERTY ESTIMATION FROM CLINICAL IMAGING DATA

Elaheh Mehdizadeh[1], Amin Pourasghar[1], Timothy Wong[1], Arvind Hoskoppal[1] and John Brigham[1]*

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ABSTRACT

A computational method will be presented for estimating the spatial distribution of mechanical properties of soft tissues within the body, particularly the heart wall, using clinical imaging data. The core innovation lies in a newly devised shape-based approach that utilizes a level-set-based measure of the difference between image-derived target and simulated tissue mechanical behaviors. This approach is an extension of prior work by the authors that used a standard discretized version of the Hausdorff distance as an objective function in an iterative approach to material parameter estimation [1]. As such, a novel level-set framework is introduced for the objective function that is differentiable and is implemented into an optimization framework to identify the material parameters that minimize the difference with respect to a “target” shape with relative computational efficiency. The adjoint method is employed to calculate the gradient throughout optimization, further enabling efficient minimization of the shape-based objective function. In additional to presenting the computational procedure, the method will be evaluated via simulated inverse problems based on estimating passive heart wall mechanical material properties from standard cardiac clinical imaging data and hemodynamics (i.e., intraventricular pressure). These computational tests consider a simplified system of a two-dimensional (slice) of the bi-ventricular wall with the diastolic process estimated by applying intraventricular pressure, and considers only elastic material properties. Assessment of the results will include the capability to minimize the shape-based objective function effectively and consistently, the accuracy of the estimated material parameters, and the effects of model error on the inverse solution estimation process. Longer-term objectives involve integrating the computational approach with more realistic in vivo conditions, including geometry and boundary conditions. Moreover, the approach will be extended to have the capability to estimate more generalized heterogenous properties and/or alternate constitutive models.

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Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FRAMEWORK FOR RISK ASSESSMENT OF POST-TENSIONED CONCRETE BRIDGES- DATA-DRIVEN STOCHASTIC APPROACH CONSIDERING LIFE CYCLE

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ABSTRACT

Incidences of premature failures PT tendons and other damages along with certain persistent factors causing these damages have raised the need for a targeted bridge risk assessment and maintenance decision making processes. The main objective of this paper is to introduce a framework for risk and reliability assessment and maintenance decision-making for in-service PT concrete bridges built around the traditional expert-elicited processes. The emphasis will be on PT bridges' most critical elements, i.e., the tendons. The target framework is expected to provide guidance for bridge engineering practitioners and owners for processes involved in data-driven risk assessment and management of the risk and safety assurance with emphasis on life cycle. The framework should offer tools and processes that are simple to use but sophisticated enough for accuracy and reliability, and for consistently carrying the stochastic approach throughout the entire process. Such data-driven approach should rely on recognition of damage modes and risk-based selection of inspection methods, probabilistic presentation of the inspection results, analysis for demand and strength, reliable deterioration models, risk and reliability formulation, life-cycle analysis for change of condition and selection of appropriate maintenance scenarios. The process should allow calibration based on expert elicitation, owner criteria, and experimental data.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND LOAD ESTIMATION OF OFFSHORE WIND TURBINE BASED ON KALMANNET

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ABSTRACT

Offshore wind turbines represent fatigue-prone structures owing to the exposure to intense and fluctuating wind loads. The accurate estimation of wind loads proves invaluable in assessing fatigue life at critical hotspots and facilitating virtual sensing capabilities. Moreover, this input estimation methodology contributes to the optimization of design processes and operational control strategies. This paper presents a novel approach for wind load input estimation utilizing KalmanNet, a hybrid framework that combines the strengths of Kalman filter (KF) and recurrent neural networks (RNN). KalmanNet shares the general recursive structure of KF, but replaces the matrix manipulation-based computation of Kalman gain (KG) with a RNN model which are trained using measured data. This hybrid approach provides a more robust and adaptive solution compared to traditional methods that rely solely on either KF or neural networks: Compared to KF, it is more robust to nonlinearity and modeling errors as the RNN-based evaluation of KG is learned from data instead of subspace matrices; Meanwhile, compared to pure data-driven neural networks, it has higher generalization and extrapolation capability. KalmanNet can be implemented either in a supervised or unsupervised manner. This study employs a supervised version, considering that this is a numerical study where the true wind loads are known. For real-world applications, true wind loads can be either estimated using strain gauge rosette, or a unsupervised KalmanNet will be adopted. The study employs the simulated data of a 6 MW offshore wind turbine to validate the effectiveness and accuracy of the KalmanNet approach for wind loads estimation.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY QUANTIFICATION OF COMPLEX STRUCTURAL CONNECTIONS THROUGH BAYESIAN MODEL UPDATING USING MODAL DATA

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ABSTRACT

Structural joints play a crucial role in the overall performance of complex engineering systems, influencing their stability, reliability, and safety. This study explores uncertainty quantification for complex structural joints, employing an efficient approach based on Bayesian model updating using modal data. There are many challenges posed by complex connections within engineering structures. They can be due to uncertainties in material properties, manufacturing processes, and environmental conditions. The analytical model developed for this research incorporates a low-fidelity simulation of complex structural connections in a benchmark laboratory steel grid. This model aims to strike a balance between computational efficiency and accuracy, enabling the exploration of a broad design space while capturing the essential characteristics of the joint behavior. By leveraging modal data obtained through experimental testing, the Bayesian model updating technique refines the analytical model to better represent the true mechanical response of the structural joint. Hence, the probability distribution of mass and stiffness parameters of the semi-rigid joints of the grid are found in a structural parameter estimation procedure. Key components of this research include a comprehensive overview of the analytical model, detailing the incorporation of uncertainty sources and the modal data-driven Bayesian model updating process. The study showcases the application of the proposed methodology to real-world structural joints, demonstrating its effectiveness in accurately characterizing the uncertainties associated with complex connections. The principal contributions of this research to the field of engineering mechanics lie in developing a robust methodology for uncertainty quantification of complex structural joints. Integrating Bayesian model updating with modal data gives engineers a powerful tool to assess and manage uncertainties in joint behavior, ultimately enhancing the design and optimization processes for complex engineering systems. This research bridges the gap between theoretical models and practical applications, offering a valuable contribution to the broader goal of ensuring the structural integrity and reliability of complex engineering structures in the face of inherent uncertainties.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A ROUGHNESS-FREE CONTINUOUS CONDITION MONITORING FRAMEWORK FOR BRIDGE STRUCTURES THROUGH A SPARSE NETWORK OF CONNECTED SMART VEHICLES

Mohammad Talebi-Kalaleh[1], Qipei Mei[1] and Mustafa Gul[1]*

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ABSTRACT

Condition monitoring of bridge structures as the lifelines of smart cities is a pivotal task. Current indirect monitoring techniques, which mainly rely on single or multiple passage of one sensing vehicle, have shown promising results and proven to have less cost compared to traditional fixed accelerometer installations. However, these methods face challenges in accurately predicting vibration response of the bridge under real-world traffic flow scenarios due to the limited time each vehicle spends crossing the bridge, yielding insufficient vibration data collection.

This research introduces an innovative, roughness-free, crowdsourced framework capable of reconstructing vertical acceleration response of the bridge at some arbitrary virtual sensing nodes. This framework employs a random selection approach among a network of connected moving sensors (vehicles). Leveraging vertical and rotational acceleration data collected from the diverse sensor-equipped vehicles traversing the bridge, along with their GPS location data, enables the prediction of bridge full-field response. The predicted accelerations are used for identifying the bridge’s mode shapes and natural frequencies, which are pivotal inputs for vibration-based damage detection techniques.

A primary innovation of this research lies in the random selection of sensing vehicles at each timestamp. Continually updating the set of selected sensing agents overcomes the data length limitations of conventional vehicle-based methods by harnessing multiple vehicles and ensuring continuous data collection. Moreover, the framework addresses roughness and operational effects, known to significantly impact vehicle-assisted structural health monitoring techniques, by utilizing residual responses from the selected agents' rear and front axles.

Comprehensive numerical studies evaluated the method's performance, simulating a three-span bridge subjected to varying surface roughness levels and traffic flow scenarios comprising two-axle vehicles with different speeds and initial locations following a normal distribution. The numerical analyses consider vehicle-bridge interaction and demonstrate the framework's efficacy in accurately predicting bridge acceleration responses, even when employing just one random agent. Notably, the method achieves a 95% accuracy rate in identifying the bridge's first three mode shapes.

Keywords: Indirect Bridge Health Monitoring, Vehicle Scanning Method, Drive-by SHM, Crowd-sensing

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTIFIDELITY GRAPH U-NET FOR PHYSICS SIMULATIONS

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ABSTRACT

Physics-based deep learning frameworks have shown to be effective in accurately modeling the dynamics of complex physical systems with generalization capability across problem inputs. While unsupervised networks like PINNs rely only on the underlying governing equations and boundary conditions, they are limited in their generalization capabilities. However, data-driven networks like GNN, DeepONet, Neural Operators have proved to be very effective in generalizing the model across unseen domains, resolutions and boundary conditions. But one of the most critical issues in these data-based models is the computational cost of generating training datasets. Complex phenomena can only be captured accurately using large enough deep networks that require large training datasets. Furthermore, the numerical error of the samples in the training data is propagated in the model errors, which necessitates the need for accurate data, i.e. FEM solutions on high-resolution meshes. Multi-fidelity methods offer a potential solution to reduce the training data requirements. To this end, we propose a novel GNN architecture called Multi-fidelity Graph U-Net, which incorporates meshes of different granularity at different levels of a graph U-Net architecture and uses outputs from these levels for training the model. We show that this approach performs significantly better in accuracy and data requirement and only requires training of a single network compared to other benchmark multi-fidelity approaches like transfer learning models. Moreover, we observe that this approach requires shallower networks compared to existing GNN models for physics simulations, thus accelerating the training time and reducing the system requirements. We show the results of our approach using two benchmark dataset - mechanical MNIST multi-fidelity data and cantilever beam with varying size and resolutions.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A TWO-WAY COUPLED FLUID-STRUCTURE INTERACTION FRAMEWORK FOR AEROELASTIC MODELING OF TALL BUILDINGS USING LARGE-EDDY SIMULATION

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ABSTRACT

Computational modeling of wind-induced vibration of structures has a significant potential for the wind-resistant design of structures that are susceptible to aeroelastic effects, such as tall buildings. When such structures experience noticeable motion-induced forces, the aerodynamic loads and their mechanical properties are coupled, thus requiring a fluid-structure interaction phenomenon to be aptly simulated. This study proposes a high-fidelity two-way coupled Fluid-Structure Interaction (FSI) framework for computational aeroelastic modeling of tall and flexible buildings using open-source software architecture. For modeling the wind flow, the Navier-Stokes equations were solved in an Arbitrary Lagrangian-Eulerian (ALE) frame of reference on a moving mesh using a large-eddy simulation. The governing equations of motion for the building structure were transformed and solved in a generalized coordinate system to improve computational efficiency. The FSI framework employs a partitioned procedure where wind and structure subsystems are solved separately, and the coupling is achieved by exchanging data at each time step. Two coupling algorithms representing "weak" and "strong" methods were investigated. Finally, the capability and efficacy of the proposed framework is demonstrated by simulating the wind-induced vibration of a tall building immersed in a turbulent atmospheric boundary layer.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VOXELATED CARBON FIBER ALIGNMENT IN POLYMER COMPOSITES: MAGNETIC STEREOLITHOGRAPHY 3D PRINTING

Drew Melchert[1] and Caitlyn Krikorian[1]*

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ABSTRACT

Controlling the alignment of filler particles in composite materials presents opportunities to optimize the mechanical response of architected components, but with current manufacturing techniques such as direct ink writing it is challenging to control alignment in lattices and other complex geometries. This work instead employs magnetic fields to align carbon fibers during stereolithography, enabling particle alignment in user-specified directions in each voxel with 75 micron resolution with minimal post-processing or interlaminar defects. The resulting fine control of anisotropic mechanical properties as a function of fiber orientation (e.g. over a range of 45% for tensile strength at 25v% fiber loading) allows optimization of reinforcement in complex printed parts, particularly for tailored anisotropic response in lattices. Computational optimization of part geometry and fiber alignment are also developed to guide design for applications using both stiff materials (aerospace) and soft materials (energy absorption).

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Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTERMEDIATE ISOLATION SYSTEM FOR EXISTING BUILDINGS

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ABSTRACT

The Intermediate Isolation System (IIS) is a variety of the classical base isolation characterised by isolation system shifted at an intermediate level along the building height; it is recently emerged within the Japanese design practice, together with several innovative schemes and hybrid or mixed solutions which blur the boundaries among the different approaches for the building response control. In particular, the IIS is also appointed as non-conventional tuned mass damper since it combines the two strategies of seismic isolation and mass damping. In IIS, indeed, the isolation hardware is utilized for mobilizing entire building portions as mass dampers characterised by large mass ratio, thus obtaining an effective and robust response control. Among the possible applications, the vertical extensions of existing buildings realized through IIS are particularly interesting, since the extension, realized on the rooftop of the existing building and equipped with an isolation system at its base, can work as a mass damper, thus reducing the seismic demand on the old structure.

The idea proposed in this presentation is to predict the elastic or inelastic response of the existing structure in the IIS configuration by means of the results of simple linear analyses. Parametric response spectrum analyses are performed on simplified two degree-of-freedom models by varying the mass ratio and the periods of both the existing building and the new isolated vertical extension. So-called IIS design spectra are derived, and the results are provided as design charts. Given the period of the existing building and the mass ratio, the period of the new isolated vertical extension is selected as the one able to obtain the required/desired response of the existing building.

For existing buildings working in the elastic field, the response of the existing structure in the extended configuration can be directly derived by utilizing the IIS design spectra as design charts. For existing building working in the inelastic field, the design charts can still be adopted, though within a more complex procedure, which accounts for two limit behaviours that the extended building exhibits in the inelastic field at to two limit values of the isolation period.

In this presentation, the general design procedure is outlined and applied to some case studies; then, the procedure is validated through the comparison with the results of nonlinear time history analyses.

ON DETERMINING STRUCTURAL WALL LAYOUT DURING THE ADAPTIVE REUSE PROCESS OF UNREINFORCED MASONRY BUILDINGS

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ABSTRACT

The adaptive reuse of unreinforced masonry buildings presents a nuanced challenge, requiring a delicate balance between structural stability and preservation goals. This study introduces an innovative computational approach aimed at identifying modifications to shear wall layouts during the adaptive reuse process. The primary objective is to redefine structural wall arrangements to accommodate new openings, offering designers flexibility in spatial arrangement modifications.

Central to this approach is the utilization of a Genetic Algorithm, inspired by evolutionary principles, as a potent tool for deriving potential layout solutions that adhere to structural requirements while facilitating the incorporation of new openings. The presentation will comprehensively explore the key components of the proposed genetic algorithm approach, including the formulation of a customized fitness function, the encoding of design variables, and the integration of structural constraints, accounting for axial and shear effects.

By systematically evolving potential solutions over multiple generations, the algorithm navigates the intricate design space to pinpoint areas within the original shear layout where material can be removed, all while respecting the unique constraints inherent to unreinforced masonry structures. The methodology's validity is demonstrated through a case study situated in a UNESCO World Heritage Site, providing tangible evidence of the practical application and success of the genetic algorithm approach in real-world scenarios.

The findings presented in this conference contribute to the convergence of structural engineering and architectural preservation, offering a systematic and efficient means of determining shear wall layouts for the adaptive reuse of unreinforced masonry buildings. The integration of genetic algorithms into the adaptive reuse process holds transformative potential, establishing a robust framework for sustainable urban development that honors and enhances the historical fabric of our built environment.

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Complex dynamics and vibration control of infrastructure exposed to single/multiple hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PRACTICAL PIECEWISE LINEARIZATION APPROACH TO ESTIMATING THE NONLINEAR HYDRODYNAMICS FOR FLOATING WIND TURBINES UNDERGOING LARGE PLATFORM MOTIONS

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ABSTRACT

Floating wind turbines (FWT) are amongst the most promising technologies to unlock substantial offshore wind resources in deep waters. To achieve the competing FWT design objectives of structural integrity and cost reduction, reliable simulation tools that capture the dominant dynamics are crucial. The potentially large platform motions induced by harsh ocean environmental loads are not in agreement with the assumption of small platform motions, which is commonly employed in popular FWT simulation tools. To capture the nonlinearities induced by large platform motions, the authors proposed a piecewise linearization approach in previous work [1], in which the wave-platform interaction problem is re-linearized frequently as the platform moves, and a state-basis transformation algorithm was developed to ensure the basis-consistency among the identified state-space models from all linearizations. While the system response for the radiation problem in heave (the vertical direction) was examined in [1] via a free-decay test, the full movement of the FWT platform leads to a substantially more complicated problem. When the platform experiences overall motions, the 6 platform forces in total are not enough to identify a state-space model that captures all dominant wave radiation effects. In light of this, a series of pressure outputs over the platform submerged surface are added. Furthermore, wave actions that are absent in [1] are necessary for the reproduction of a realistic environmental condition. However, the existing wave excitation model is often interpreted as acausal despite the causal wave propagating process. In this work, the assumptions that lead to this loss of causality are highlighted, and the introduction of pressures naturally yields a causal model. This new pressure-based piecewise linearization framework is implemented in a Simulink FWT model, and an open-source boundary element method code, Nemoh, is used to provide the radiation and excitation forces/pressures at each linearization. A 5-MW ITIBarge FWT is tested under moderate wave actions to demonstrate the efficacy of the newly proposed approach. The platform responses obtained are compared to the common practice of linearizing only around the equilibrium platform position. The capability of the new approach to conduct a fast and robust evaluation of the nonlinear hydrodynamics for FWTs makes it an effective and practical tool for FWT dynamic analysis and design optimization.

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Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BOUND CONSTRAINED OPTIMIZATION USING LAGRANGE MULTIPLIER FOR A LENGTH SCALE INSENSITIVE PHASE FIELD MODEL

Li Meng[1], Hsiao Wei Lee[1], Alireza Ashkpour[1] and Ahmad Najafi[1]*

[1]Drexel University

ABSTRACT

The classical phase field model with second order geometric function α(d)=d^2(i.e., AT2 model), has wide applications in static and dynamic scenarios for brittle materials, but nonlinearity and inelasticity are found in its stress-strain curve. The phase field model with linear geometric function α(d)=d (i.e., AT1 model), can avoid this, and a linear elastic threshold is available in its stress-strain curve. The d∈[0,1] in these geometric functions is a damage factor to represent the state of material. However, both AT2 and AT1 models are length scale sensitive phase field model, which could have difficulty in adjusting fracture strength and crack band at the same time through a single parameter (length scale). In this study, a generalized quadratic geometric function (linear combination of AT1 and AT2) is used in phase field model, where the extra parameter in this geometric function makes it a length scale insensitive phase field model. Similar to the AT1 model, negative phase can happen in the proposed generalized quadratic geometric function model. To solve this problem, a bound constrained optimization using Lagrange multiplier is applied, and the KKT conditions change from strain energy and maximum history strain energy to phase and Lagrange multiplier. A single element analysis, a bar under cyclic loading, mode Ⅰ Brazilian tensile test, and mixed mode PMMA tensile test verify the feasibility of the proposed phase field model. From these simulations, the proposed Lagrange multiplier works well on the irreversibility constraint of fracture propagation. For the proposed length scale insensitive phase field model, it can provide a linear elastic threshold, and a narrower crack band can be obtained, compared to the other two phase field models (i.e., AT1 and AT2).

Keywords: Phase Field Model, Length Scale Insensitive, Bound Constrained Optimization, Lagrange Multiplier

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A COMPUTATIONAL STUDY OF FRACTURE NUCLEATION AND PROPAGATION USING THE REVISITED PHASE FIELD MODEL

Li Meng[1], Hsiao Wei Lee[1], Alireza Ashkpour[1] and Ahmad Najafi[1]*

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ABSTRACT

The phase field model with linear geometric function α(d)=d (i.e., AT1 model), can have a linear elastic threshold in its stress-strain curve, which is supposed to better model brittle fracture, compared to the classical phase field model with second order geometric function α(d)=d^2(i.e., AT2 model). And with the split of strain energy, anisotropic AT1 phase field model can better capture the different response between tensile load and compressive load than isotropic AT1 phase field model. Even though both AT2 and AT1 models can give a correct tensile strength, they are not able to predict compressive strength very well, which could lead to some discrepancies between simulation and experiment. In this study, these two models are compared with a revisited phase field model from Kumar et al. [J Mech Phys Solids 142:104027, 2020]. In this model, by following the Drucker-Prager strength surface and introducing an external driving force, an exact relation between tensile strength and compressive strength can be obtained. Apart from capturing tensile strength and compressive strength, a generalized external driving force is derived to adjust the fracture stress under hydrostatic condition to better match with material's property. Notch plate tensile test, tensile bar test, three-point bending test, Brazilian tensile test, and mixed-mode PMMA tensile test verify the feasibility of the revisited phase field model. From these simulations, the revisited phase field model can capture both tensile strength and compressive strength well, and the fracture pattern obtained from this model agrees with experiment.

Keywords: Revisited Phase Field Model, Fracture Nucleation, Fracture Propagation, Computational Study

Recent advances in mechanical energy harvesting and its applications in structural health monitoring and control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELECTROMAGNETIC ENERGY HARVESTER FOR RURAL RAILWAY CROSSINGS

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ABSTRACT

Railway crossings play a pivotal role in the seamless operation of transportation networks, ensuring the safe passage of trains at road intersections. Effective railway crossings contribute significantly to minimize traffic congestion, to enable the efficient flow of both vehicular and railway traffic. Because safety is essential, potential accidents between trains and road users must be prevented. By implementing advanced signaling systems, barriers, and warning devices, these crossings provide essential safeguards to prevent accidents and collisions between trains and road vehicles, thus protecting the lives of commuters and railway personnel. However, when it comes to railroad crossings in rural areas, a simple and effective means to generate power becomes a challenge. This study details the research conducted to develop a power generator at railroad crossing which makes use of oscillating magnets in the vicinity of copper coils. The proposed design is simply a spring-mass system in which the mass is a cylindrical magnet moving within a copper coil. A passing train provides an attractive force between the magnet and each wheel which excites the oscillations. The magnetic field interaction between the magnet and the copper coil generates an induced voltage that can be stored in batteries and used to power railway crossing lights when needed. A finite element model of the harvester system is used to quantify the electromechanical behavior and to optimize its configuration in order to maximize the power generation. This method of generating power is simpler and less expensive than previous approaches and would require less maintenance. It will also mitigate limitations associated with power generation for railroad crossings at rural locations.

NORMAL STRESS VARIATION AND PORE PRESSURE RATE EFFECT ON A RATE AND STATE FRICTIONAL FAULT

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[1]Northwestern University

ABSTRACT

This study is inspired by the work of French et al. (2016), that conducted axisymmetric compression (AC) and lateral relaxation (LR) tests on saw-cut sandstone. We use a spring-block model with rate and state frictional (RSF) slip to examine the effects of effective normal variations in fluid saturated specimens loaded in AC and LR. RSF is defined by characteristic weakening distance d_c and constitutive parameters a and b. If a-b<0, the system is linearly unstable if the spring stiffness is less than a critical value k_c. RSF model usually assumes constant normal stress acting on the frictional surface. AC consists first in applying a constant hydrostatic stress, then increasing the axial load. LR is performed by first applying a constant hydrostatic stress, then reducing the lateral stress. In both tests, normal stress on the inclined saw-cut surface is not constant. We explore the effects of these normal stress changes in fluid saturated specimens for different pore fluid pressure rates of fluid injection and diffusivity. Results show that normal stress changes generate antithetical effects on AC and LR. In AC, effective normal stress increases enlarge the instability range because k_c increases. In LR, effective normal stress decreases stabilize the frictional response as k_c diminishes. Rapid slip events occur less often and are greater in magnitude in AC and more frequent and smaller in magnitude in LR. In drained conditions, our results agree with French et al. (2016): during their limited experimental time, they did not get any dynamic events in AC while observing several slip events in LR. The latter case suggests that rapid slip events correlate with increases of fluid pressure in the reservoir. Simulations show that frictional response depends on fluid pressure increases for both AC and LR: for low pressure rates, the reservoir pressure does not change appreciably and frictional response is dominated by RSF effects. For higher injection rates, RSF effects interact with pore pressure increases and the frictional sliding progressively stabilizes. The response also depends on the non dimensional diffusivity c^*, the ratio of the RSF timescale to the fluid diffusion one. For low c^*, fluid diffusion occurs slowly: dilatation is inhibited and pore pressure drop decays slowly. Consequently, k_c decreases faster and stabilizes the frictional response. For higher c^*, fluid diffusion occurs rapidly and the frictional response is dominated by RSF effects.

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Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HEAT TRANSFER ANALYSIS OF WATER SERVICE LATERALS DURING WILDLAND-URBAN INTERFACE FIRES

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ABSTRACT

In recent fire seasons, wildfires have been damaging water distribution system components within wildland urban interface (WUI) communities. Post-wildfire investigations have resulted in the detection of volatile organic compounds (VOCs) within the water distributions systems. The source of these compounds is an active research topic, with one potential mechanism being the thermal degradation of pipe materials either from direct heating through the soil or the introduction of hot air to the inside of the pipe due to depressurization of the water system during the fire. To study these heating mechanisms, heat transfer models were developed to calculate temperatures of the pipe material throughout a real-fire condition. These models are being validated and benchmarked against laboratory tests. The transient heat transfer models were adapted from Richter et al.'s 1-dimensional, steady state model that treats the soil as a semi-infinite solid [1] and have non-homogenous boundary conditions imposed by a real fire situation. The soil mass model uses many of the same assumptions as those present in Richter et. al. However, it is no longer being treated as a semi-infinite solid since the data being used is associated with a series of lab tests. Additionally, the model looking at heat transfer from hot air inside the pipe is 2-dimensional throughout the cross-section of the pipe being analyzed.

Through the development of these models, researchers will be able to simulate a variety of realistic fire conditions to better understand what conditions would lead to water contamination due to thermal degradation of the pipe materials. These types of models can be coupled with wildfire propagation models being developed by others such that risk assessment of community infrastructure is possible within the WUI.

Tropical cyclone induced winds, surge-wave, flooding and impacts on infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FLOOD PERFORMANCE EVALUATION OF PROCESS PIPELINES USING FINITE ELEMENT ANALYSIS

Md Manik Mia[1] and Sabarethinam Kameshwar[1]*

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ABSTRACT

The purpose of this study was to investigate the flood performance of pipelines attached to above ground storage tanks (ASTs) by performing finite element analysis and developing fragility models. Although, recent studies highlighted the vulnerability of process pipelines, the literature is currently lacking the flood performance of process pipelines. Besides, the design guidelines are deficient with regards to flood related failure of pipelines. Also, the contribution of pipelines in resisting tank flotation or sliding is unknown since most studies ignored the pipe resistance while performing fragility assessment of ASTs for these failure modes. To address these gaps, this study investigated fragility assessment of pipelines during flood events for four common pipe configurations observed in process industry. Using Progressive Latin Hypercube Sampling (PLHS), design parameters such as pipe diameter and elbow radius, pressure, relative density of water and steel, yield stress, surge height, water velocity, flood inundation depth, and hydrodynamic coefficient were sampled uniformly. In this study, finite element software LS – Dyna was used to investigate the response of pipelines during flood events. Herein, one end of the pipe was fixed and the other end was displaced in a displacement controlled analysis to represent tank flotation or sliding. For each design parameter combination, maximum stress in pipe was determined from finite element analysis and was compared against two different failure thresholds corresponding to material yielding and rupture. Step wise logistic regression was used in order to develop fragility models. This method was repeated for four different pipe configurations and fragility curves were developed. The results revealed that for smaller tanks exposed to low to moderate flood depths, pipe resistance against flotation and sliding are significant and can't be neglected.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FRAMEWORK FOR SUSTAINABLE BUILDING MATERIALS USING LIGNIN BIOPOLYMER BOUND SOIL COMPOSITES

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ABSTRACT

Biopolymer bound soil composites (BSCs) are a new class of sustainable materials that have been explored as alternatives towards soil improvement and other construction applications using biological binders, many of which can be sourced from waste streams. However, current BSC design does not cover methods for re-using BSCs at the end of life. This work aims to address these limitations by introducing a novel framework for the life cycle design of sustainable hydrophobic Lignin BSCs. Lignin is a prime candidate for BSC development because of its abundance and availability in areas with high demand for cement. Additionally, as Lignin is a hydrophobic biopolymer, its use in BSCs will help provide increased durability against external exposure to moisture or precipitation.

A framework for the life cycle design of Lignin based building materials is introduced in this work, where a non-aqueous solvent (dimethyl sulfoxide) is mixed with aggregate and Lignin binder to form Lignin BSCs. As is the case for other mass-produced construction materials (ordinary Portland cement and asphalt concrete), the design of BSCs is driven by key metrics of material composition that relate to target material properties. Experimental samples (cylinders of height = 52.0 mm and diameter = 25.4 mm) were developed for four main types of lignin at different mix designs. Compressive testing of these samples was carried out, and predictive values of biopolymer content, biopolymer saturation ratio, and dry bulk soil densities were analyzed. These features are used to develop a material design guide for different types of lignin, which allows for the design of Lignin BSCs for a given target compressive strength. Results from these samples indicate that Lignin BSCs can be used for non-load bearing applications according to ASTM C55.

To determine the carbon footprint of Lignin BSCs, a life cycle assessment was conducted comparing a unit-sized Lignin BSC block to those made of conventional materials. The results from the analysis showed that Lignin BSC is a potentially carbon negative material, because carbon rich lignin is embodied into the BSC. An estimate of the life cycle carbon footprint of Lignin BSCs was also determined, which allows for the design of Lignin BSC materials for a target life cycle carbon footprint and a target compressive strength.

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VARIABILITY RESPONSE FUNCTIONS FOR CERTAIN PROBLEMS IN CLASSICAL ELASTICITY

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ABSTRACT

A major issue in stochastic structural mechanics is the difficulty in validating the probabilistic description of the random system parameters assumed in many studies. investigations usually require extensive sensitivity analyses with respect to these parameters, and this can lead to prohibitive computational cost and possible loss of insight on their relative effect.

In order to address the issues mentioned above, the concept of the Variability Response Function (VRF) has been proposed in the past as a means of systematically capturing the effect of the spectral characteristics of the random system parameters [1]. The existence of the classical VRF can been rigorously derived only for the case of linear elastic, statically determinate structures; on the other hand, for many other structural mechanics problems, the derivations require the assumption of small parameter variability. Either way, the classical VRF is a purely deterministic function that is independent of the probabilistic characteristics of the system parameters [2,3,4,5,6].

In this work, we derive classical VRFs for certain problems in classical elasticity. These include plane-strain, antiplane-strain, and plane stress problems. In all cases, we use a rigorous formulation that takes advantage of some underlying mathematical symmetry to render the problem statically determinate and thus amenable to the classical approach. It is emphasized that all VRF derivations were performed without any approximations or series expansions, so their validity is not limited by the magnitude of the fluctuations of the relevant random field. We also believe this is the first time that these types of problems have been addressed in the VRF literature.

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Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL PERFORMANCE OF THREE-LAYER PARTICLEBOARDS WITH WASTE FIBER REINFORCEMENT: A REVIEW

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ABSTRACT

With the increasing demand for wood driven by population growth and urbanization, this study explores the potential of three-layer particleboards reinforced with waste fibers as a sustainable and eco-friendly alternative in building material technology. It focuses on various waste fibers such as sisal, bagasse, leather shavings, and waste papers, assessing their impact on the structural properties of particleboards. The research thoroughly evaluates key mechanical properties such as the modulus of rupture (MOR) and modulus of elasticity (MOE), as well as essential physical properties like water absorption (WA) and thickness swelling (TS). This investigation delves into the innovative use of organic and natural bio-waste particulates as reinforcing agents in polymer composites, specifically examining their role in enhancing particleboard characteristics. A significant finding of this study is that the enhanced particleboards not only meet but sometimes exceed, the minimum standards set by various international guidelines for general purposes. This indicates that it is feasible to replace traditional wood fibers with certain organic waste materials while maintaining or even improving the performance of conventional particleboards. This advancement is particularly relevant to the construction industry, as it suggests that these improved particleboards can be effectively used as sustainable structural materials. By utilizing waste fibers, it not only aligns with global sustainability goals but also provides a practical solution for waste management across multiple industries. Consequently, this research represents a significant step forward in the development of building materials that support eco-friendly construction practices and contribute to the circular economy.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS OF PRESTRESSED FIBROUS NETWORK MATERIALS SUBJECTED TO LOCAL CONTRACTION

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ABSTRACT

Random fibrous networks serve as fundamental structural components in a varied range of materials, covering both biological and non-biological domains. Notable examples include paper, rubber, fabric, cell cytoskeleton, and the extracellular matrix (ECM). Beyond their crucial role in maintaining the structural integrity of these materials, these fibrous networks play a key role in facilitating various inherent processes. For instance, in biological materials, random networks significantly contribute to processes like homeostasis, tissue morphogenesis, and wound healing, having a major influence on the behavior and processes of these materials. Recognizing the important functions of fibrous networks in materials, researchers have focused towards studying the mechanical characteristics of such networks. A specific area of interest within the domain of random network research is the biological networks of the ECM, composed of collagenous random fibers. These networks exhibit remarkable properties, including nonlinear strain stiffening and the long-range transmission of forces and displacement, distinguishing them from their non-biological or regular network counterparts. Recent studies have also highlighted the fact that these networks accommodate residual stresses or prestress within them. These prestresses have been observed to influence the behavior of random networks, leading to changes in overall network stiffness and the emergence of strain stiffening behavior. However, past studies investigating long-range transmission within random networks have less considered prestress and its overall effect. Moreover, when examining the structure of the ECM, it becomes apparent that it is not a singular network structure composed only of collagen but is a composite structure made up of multiple interpenetrating fiber network structures. Thus, it is important to consider this aspect of the ECM when modeling and analyzing their overall mechanical behavior. This study investigates long-range transmission of deformation field within prestressed single fiber networks and composite random fiber network structures subjected to local contractile forces. It was observed that the presence of prestress certainly affects the expanse of deformation field in the fibrous networks. Additionally, the influence of different network microstructural properties such as average network connectivity and fiber bending rigidity were fully investigated. It was found that decreasing the bending rigidity of individual fibers leads to an increase in the propagation of displacement due to the local deformation at the center of the network. The investigation aims to understand how these networks behave in their natural environment, and their contributions to material properties, assisting in development of substances that can mimic or exceed natural networks, enabling different applications.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FULL-SCALE SHAKE TABLE COLLAPSE TESTING OF A THREE-STORY POST TENSIONED MASS TIMBER ROCKING WALL BUILDING

Prashanna Mishra[1], John W. Van De Lindt[1], Andre Barbosa[2], Patricio Uarac[2], Shiling Pei[3], Steve Pryor[4], Steven Kontra[2], Barbara Simpson[5], Arijit Sinha[2] and Tara Hutchinson[6]*

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ABSTRACT

Understanding and quantifying the collapse behavior of new seismic force resisting systems (SFRS) is key to incorporating them into modern building standards such as American Society of Civil Engineers Structural Engineering Institute (ASCE/SEI) Standard 7. A series of mass timber building projects which included full-scale testing took place on the world's largest outdoor shake table in San Diego, California during 2023-2024 (NHERI Tallwood and NHERI Converging Design). At the end of these two groundbreaking projects, which included full-scale ten-story and six-story test programs, each with multiple phases over several months, the upper stories were removed resulting in the creation of a three-story building representative of a state of the art post-tensioned mass timber construction. The lateral force-resisting system (LFRS) of the three-story building incorporates mass timber panels as rocking walls with U-shaped flexural plates (UFPs) distributed throughout the building height to contribute to energy dissipation capabilities. The post-tensioning rods provided re-centering capabilities for each wall and were decoupled from the lateral motion of the floor and roof diaphragms. This presentation will explain the design of the system and its transformation from the taller building to the three-story collapse test specimen highlighting the seismic intensity needed to collapse the building, and the ability of a corresponding analytical model to predict capacity and collapse behavior. This study may have implications on procedures used to incorporate new LFRS into building codes in the United States including, but not limited to, FEMA P695.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL EVALUATION OF COSSERAT MODEL DERIVED FROM GRANULAR MICROMECHANICS APPROACH

Anil Misra[1]*

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ABSTRACT

Granular materials are composed of nearly rigid elements (or grains) in which the elastic strain energy is stored in deformable interconnections or interfaces between the grains. Such systems can be described using continuum models based upon the granular micromechanics approach (GMA) [1-2]. In particular, GMA, has the ability to reveal the connections between the micro-scale mechanisms that store elastic energy and lead to particular emergent behavior at the macro-scale. Recently, we have exploited the GMA paradigm to design metamaterials that follow the granular motif (see for example [3-5]). 3D printing was used to fabricate the designed systems. These were then tested under tension or compression and their deformation analyzed using digital image correlation (DIC). In this presentation, we will describe the salient features of GMA and the findings of the experimental effort, particularly in relation to the grain motions and the emergent macro-scale force-displacement response.

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Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EMERGENCE OF CRITICAL STATE PREDICTED BY CONTINUUM MODEL BASED UPON GRANULAR MICROMECHANICS APPROACH

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ABSTRACT

The mechanical behavior of sheared granular materials formed of non- (and nearly non-)cohesive is characterized by the critical state in which deformation occurs without change of material volume or shear stresses. Modeling of such behavior requires the description of collective mechanical behavior of very large number of grains which are storing elastic energy as well as dissipating energy though irreversible deformations (plasticity) and loss of contacts (damage). While discrete particle-based simulations (such as DEM) have gained wide attention for investigating such materials, continuum models remain the most feasible and desirable. However, to be representative, continuum models must properly account for the granular nature of the material. Granular micromechanics approach (GMA) provides a paradigm that bridges the grain-scale models to appropriate continuum models [1-2]. Recently this approach has been further refined for damage and plasticity modeling under finite deformations [3]. Objective kinematic descriptors have been obtained for grain-pair relative displacement in the framework of second gradient continua. Additionally, Karush–Kuhn–Tucker (KKT)-type conditions have been derived for grain-pair damage evolution using purely mechanical arguments based upon a non-standard hemivariational approach [3]. This presentation will discuss the salient points of the modeling approach with particular attention to the emergence of critical state due to the evolution of effective damage and plasticity at the grain-scale.

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AI-enhanced probabilistic reliability assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL MACHINE LEARNING FRAMEWORK FOR IMPROVED PREDICTIONS OF PEAK RESPONSE TO DYNAMIC LOADS

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ABSTRACT

Extreme events such as earthquakes and hurricanes cause widespread damage and disruption to infrastructure assets such as buildings and bridges. Accurate extreme event risk and resilience assessment requires portfolio-level fragility functions of these assets, which establish functional relationships between a relevant peak response quantity, also known as the engineering demand parameter (EDP), and select features characterizing the hazard. Given the computational demands of analyzing several statistical combinations of hazard and structural features, while running nonlinear time history analyses for each combination, surrogate demand models relating peak EDP to relevant intensity measures (IMs) of the input time history are popular. Although IMs such as peak ground acceleration (PGA), spectral accelerations at salient time periods (e.g. 0.1 seconds, 0.6 seconds, 1.0 second) for earthquake hazards and maximum average gust and sustained wind speeds for wind hazards have been traditionally considered to be effective IMs, there is no guarantee that they are the best predictors of peak EDP. To address this, we propose a two-layer neural network model; the first layer (NN1) consists of a neural network that processes the hazard time history and extracts a desired number of features (meta-IMs), which are used as inputs to the second layer neural network (NN2) along with structural characteristics to predict peak EDP. By training NN1 and NN2 simultaneously to minimize the losses on the peak EDP, we essentially allow the algorithm to autonomously select meta-IMs with the best predictive power rather than choosing IMs a priori. The proposed framework affords the following major advantages.

1. Adaptability: It can be applied to various hazards (e.g. earthquakes, winds) irrespective of the length of time history.
2. Flexibility: The number of pseudo-IMs picked by NN1 and the hyperparameters of NN1 can be tuned to further improve model performance.
3. Improved Performance: It provides better predictive accuracy, particularly for atypical time histories (e.g. high frequency content shaking, long duration winds).

The proposed framework is demonstrated on simple case study examples of 2-dimensional RC and Steel frame structures, using a single neural network with traditional IMs as the baseline. Furthermore, alternative a priori dimensionality reduction techniques such as Principal Components Analysis (PCA), t-Stochastic Neighbor Embedding (t-SNE), Singular Value Decomposition (SVD), Laplacian Eigenmaps (LE), Diffusion Maps (DMs) and Neural Network Autoencoders to select meta-IMs are also compared to the proposed framework.

MACHINE-LEARNING ASSISTED DAMAGE STATE IDENTIFICATION FOR DETERIORATING BRIDGES

Athanasia Kazantzi[1], Sokratis Moutsianos[2], Konstantinos Bakalis[1] and Stergios-Aristoteles Mitoulis[1]*

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ABSTRACT

Bridges are critical elements for the seamless functioning of our societies. Bridge closures have a direct impact on the operation of the served transport network as well as cascading consequences on the interdependent networks and systems. Despite the significant efforts that are put towards monitoring, routine maintenance and proactive restoration, bridge closures are still happening. Furthermore, many bridges have reached their end-of-life whereas at the same time are subjected to increased traffic loads and climate-change aggravated hazards. One of the main failure mechanisms when it comes to ageing prestressed concrete bridges, is the deterioration of their material properties and in particular the creep and shrinkage of concrete as well as the corrosion of tendons. Especially the damage of tendons is an exceptionally challenging source of deterioration to detect, since tendons are not always easily accessible, and their state is not interpretable without invasive inspections. This is a capability gap that eventually leads to the problem being unnoticed until large deflections are observed, or a catastrophic failure occurs−in many cases with little warning.

To address the aforementioned problem and facilitate the implementation of an early reactive protocol, a novel machine learning-driven approach for undertaking a first-order bridge damage state assessment was developed and demonstrated on the basis of a case-study. The case-study was selected to be a landmark balanced cantilever bridge located in the North-West of Greece that was recently closed to undergo structural interventions due to large deflections that were observed on its balanced cantilever deck. The methodology was built upon the development of a finite element model of the bridge and the evaluation of the deck deflections. In doing so, several plausible damage patterns were considered that account for deterioration in the concrete Young's modulus and tendon losses due to corrosion. Through analysing bridge samples reflecting variable damage conditions, a dataset of structural responses was generated, and drift-based fragility functions were obtained. The database developed was then exploited as a training set, to enable, via utilising the k-Nearest Neighbours machine learning algorithm, a rapid damage state identification for the investigated bridge should the defections of its deck and the concrete Young's modulus are known. The novelty of the proposed methodology is its ability to interpret vertical deflections, associated with tendon loss, into a bridge damage level without having to engage thorough inspections that are usually not practically feasible during routine inspections or continuous monitoring.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DIGITAL TWINNING OF OFFSHORE WIND TURBINES USING VIBRATION MEASUREMENTS

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ABSTRACT

This presentation highlights our latest applications of physics-based and data-driven digital twins for monitoring and performance assessment of offshore wind turbines (OWTs). Physic-based digital twinning is performed through Bayesian model updating and Hierarchical Bayesian model updating where uncertain parameters of numerical models are estimated using measured data. The Bayesian inference approach provides the probability distribution of updating parameters as well as the modeling errors. Model updating was performed on two operational OWTs, one on a jacket support structure at the Block Island Wind Farm in Rhode Island and the second on a monopile in an undisclosed windfarm. Data-driven digital twinning is performed through sparse Gaussian Processes to infer the strain and moment response of the monopile OWT at its tower-base (as measured by strain gauges) using environmental and operational conditions from SCADA as model inputs. This modeling will enable the strain estimation of offshore wind turbines that can inform the fatigue and remaining useful life of the turbine. Furthermore, a Long Short-Term Memory network, which is a type of Recurrent Neural Network is fitted using measured training data to provide the wind speed at nacelle hub when vibration measurements on the tower are available. In another study, a transfer learning strategy is evaluated for virtual sensing of an OWT using measurements on another turbine in the same farm. The transfer learning study is implemented using the experimental data collected on two instrumented OWTs located in the Coastal Virginia Offshore Windfarm (CVOW).

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NEW PARADIGM FOR MULTIPHYSICS AND NON-LINEAR MECHANICS MODELING: INTEGRATED FINITE ELEMENT NEURAL NETWORKS (I-FENN)

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ABSTRACT

More complicated coupled models are needed than ever before due to the increasing complexity of the processes that computational mechanics methods are being used to model. One of the numerous difficulties with such models is their extremely high computational cost. Recent developments in scientific machine learning (SciML) have drawn more attention as potential substitutes for more traditional numerical techniques like FEM. Although SciML models have yielded some concrete and encouraging findings in computational mechanics, they are currently hindered by fundamental issues that limit their ability to become rigorous alternatives to standalone numerical solvers. Our team developed a novel technique called Integrated Finite Element Neural Network (I-FENN) in response to these difficulties. The suggested strategy aims to combine the recently developed deep learning techniques with conventional FEM solvers. The fundamental premise is to break down coupled problems so that a neural network can be trained to predict one part of the physical processes. The trained network is then integrated into a generic FEM solver in a way that makes it resemble a standard user-defined material model. Because of the reduced set of equations, the resulting coupled solver is anticipated to be substantially faster than standard mixed FEM, and it may even exhibit faster convergence in the case of non-linear models. Here, we demonstrate two uses for I-FENN: simulating gradient non-local damage mechanics and fully coupled transient thermoelasticity.

For gradient damage, the neural network is first trained to predict the nonlocal strain from the local strain, which represents the solution to the gradient nonlocal diffusion equation. The network output of the non-local strain is then integrated into the local fault resolution system. Thus, the resulting I-FENN algorithm provides a solution of a non-local damage model cheaper than a local one. In the case of transient thermoelasticity, the network is trained to predict the temperature based on the solution of the thermal energy balance equation. The output temperature is then fed into a traditional momentum balance FEM solution. Thus, the resulting I-FENN solver solves the coupled thermoelasticity model at the expense of the uncoupled model. Different types of networks have been investigated, including physics-informed, temporal convolutional networks, and variational-based networks. The presentation covers the various types of developed networks, their convergence and numerical behavior, as well as the efficiency and scale of the computational savings as the studied models grow.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMOMECHANICAL ENHANCED FINITE ELEMENT METHOD WITH PHASE TRANSFORMATION FOR FAULT MODELING IN DEEP-FOCUS EARTHQUAKES

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ABSTRACT

Deep-focus earthquakes, occurring approximately 350 to 700 kilometers deep in the Earth, occur under extreme thermomechanical conditions including high temperature and high pressure along with a geological diversity of minerals, which make the mechanical behavior of seismic prone zones very complicated. The causes of these events have been investigated during recent years by numerical and experimental approaches but still remain a puzzle for scientists. Phase transformation is theorized to be one of the complex primary origins of faulting of deep-focus earthquakes. This study introduces an advanced thermomechanical finite element model, rooted in the standard Assumed Enhanced Strain (AES) framework for the analysis of deep earthquakes. The AES allows for the robust addition of discontinuous displacement to standard finite element shape functions, eliminating the need for extra global degrees of freedom. The advanced model at the macroscale simulates the role of olivine to spinel transformation in the evolution of large-scale faults. The model is utilized to detect the formation of deep earthquake faults in narrow strain localization zones. These zones may undergo softening as a post-localization process, a phenomenon crucial for understanding fault generation through crack propagation and frictional sliding under deep seismic loading. Validation of the model's efficacy involves extensive simulations, benchmarked against observed fault behavior in historical deep earthquakes. The results demonstrate the model's capability to predict fault mechanisms, offering a valuable tool for seismic hazard assessments in regions prone to deep earthquakes.

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Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING MATERIALS WITH PRESTRESSED THIN AND STIFF REINFORCEMENTS OF CIRCULAR CROSS-SECTIONS

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ABSTRACT

Thin and stiff reinforcements are used in composite materials in order to improve their overall properties. In this talk, we present a study of mechanical processes of stress transfer that occur in materials containing reinforcements whose cross-sections have forms of circular arcs. The Gurtin-Murdoch and Steigmann-Ogden theories of material surface are used for modeling purposes. The problems are considered in plane strain setting and the governing equations, including the conditions for the fields across the arc and those at its tips, are reviewed. Exact integral representations for the elastic fields everywhere in the material systems are provided. The problem is further reduced to the system of real variables hypersingular boundary integral equations in terms of the two non vanishing components of the arc's surface stress tensor. The components are then approximated by the series of trigonometric functions that are multiplied by the square root weight functions to allow for automatic incorporation of the tip conditions. The system of linear algebraic equations is set up and solved using a standard collocation method. The numerical examples are presented to illustrate the influence of dimensionless parameters with the main focus on the study of curvature-induced effects.

Novel Methods in Engineering Mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING PERFORMANCE OF SEMI-FLEXIBLE PAVEMENTS THROUGH SELF-COMPACTING CEMENT MORTAR AS CEMENTITIOUS GROUT

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ABSTRACT

This research investigates the performance enhancement of semi-flexible pavements by incorporating self-compacting cement mortar as a cementitious grout. The study is divided into three phases for comprehensive evaluation.

Phase 1: Formulation of Porous Asphalt Mixture

In the initial phase, a porous asphalt mixture is formulated with a target voids content of 25-30%. The goal is to achieve optimal interconnected voids that facilitate effective penetration of self-compacting cement mortar. The mixture's compliance with porous asphalt performance standards is ensured through tests such as marshal stability, indirect tensile strength, contabro test, and draindown test.

Phase 2: Formulation of Self-Compacting Cement Mortar

The second phase focuses on creating a self-compacting cement mortar with high workability and superior penetration capabilities. This mortar is designed to fill the interconnected voids within the porous asphalt mixture. The formulated mortar's characteristics are assessed through tests like mini V funnel flow time, slump flow mini cone, as well as mechanical properties such as compressive strength, bending strength, and shrinkage strength.

Phase 3: Performance Evaluation of Semi-Flexible Pavement

In the final phase, the performance of the semi-flexible pavement is thoroughly studied. Various tests, including marshal stability, indirect tensile strength, high-temperature bending, low-temperature bending, resistance to rutting, and fatigue life, are conducted to assess the effectiveness of the self-compacting cement mortar-enhanced pavement.

This research aims to contribute to the optimization of semi-flexible pavement performance by utilizing self-compacting cement mortar as a cementitious grout, thereby enhancing the overall durability and longevity of the pavement structure.

Plan the future: Innovations in advanced cementitious materials and sustainability
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TAILORED ULTRA-LOW-CARBON CONCRETE ENABLED BY NANOCARBON ADDITIVES PRODUCED FROM RECYCLED KILN CO2

Hongyu Zhou[1]*, David Wood*[2]*, Ehsan Mohseni**[1] *and Anna Douglas*[2]

[1]*University of Tennessee*
[2]*SkyNano Technologies*

ABSTRACT

This research explores a permanent carbon sequestration solution to produce affordable multiwall carbon nanotubes (MWCNTs) and other nanostructured carbon products for incorporation into concretes that can take advantage of their unique properties to ultimately form high performance cement-based products and low carbon-footprint concrete. The MWCNT production is based on the indirect electroreduction of industrial waste-sourced CO2 mediated by molten salt electrolysis. The captured CO2 is then used to chemically regenerate the molten salt electrolyte by converting excess oxide ions back to carbonate ions. This presentation discusses the techniques to disperse CO2-derived nanocarbon materials in cementitious composites.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENGINEERING MECHANICS OF SUTURE INTERLOCKING MECHANISM IN CEMENTITIOUS HARD-SOFT COMPOSITES BY DESIGN AND ADDITIVE MANUFACTURING

Dana Daneshvar[1], *Mahsa Rabiei*[1], *Aimane Najmeddine*[1] *and Reza Moini**[1]

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ABSTRACT

Nacre is a distinct natural composite example that uses a small amount of organic matrix to achieve damage-resilient characteristics. It exhibits a high fracture toughness and strain-at-failure, compared to the constituent brittle aragonite tablets. However, these types of composites are not fully realized in civil infrastructure. Geometrically patterned interfaces are among the common motifs in nature that enhance mechanical properties and energy absorption. More specifically, dovetail joint blades are one of the key features in nacre that provide tablet pull-out and prevent brittle failure upon tablet sliding. Engineering the tablet pull-out, however, requires an accurate design of the joint's geometry which can benefit from digital fabrication techniques. For instance, robotic additive manufacturing offers an improved ability to define, design, and achieve geometrically complex tabulated materials and interfaces.

Here, we propose the use of hard cementitious and soft hyperelastic multi-materials to enable mechanisms of toughening and strengthening into otherwise brittle materials. To engineer the strength and toughness of the bulk, interlocking and non-interlocking mechanisms were enabled using suture architecture, with various lock angles ($\theta = 25 - 45°$) and junction gap width ($w = 1\text{-}3$ mm). A grasshopper algorithm was also developed to generate the toolpath for a Scara robot arm.

Depending on the lock angle and the gap width, two competing mechanisms were observed, namely pull-out and brittle fracture in the cementitious part. A double-peak response (interfacial debonding ahead of brittle failure) is facilitated by using a hyperelastic (PVS) material at the interlayer, postponing the immediate fracture of the brittle component and hence, absorbing more energy, without sacrificing the strength. It was found that a combination of low lock angle and wide junction gaps provided the ability to efficiently trigger the pull-out mechanism and hence dissipate high amounts of energy at high strains, while avoiding catastrophic failure. The findings indicate that at a sufficiently low lock angle and large gap width, interlocking and sliding lead to a significant increase in work-of-failure by up to 60 times compared to those counterparts without hyperelastic interlayer. Additionally, a numerical analysis was conducted to understand the sliding and interlocking mechanisms using our recently developed fracture-based framework coupling phase-field and CZM. The findings provided firsthand insight into the mechanics of hard tablets and soft interlayers, and the role of multi-materiality and geometrically induced pull-out toughening mechanism at the materials level.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDRESSING CHALLENGES IN REGIONAL SEISMIC RISK ASSESSMENTS IN BRITISH COLUMBIA: M9 CASCADIA SUBDUCTION ZONE EARTHQUAKES, DEEP SEDIMENTARY BASIN AMPLIFICATION AND NON-DUCTILE REINFORCED CONCRETE SHEAR WALL BUILDINGS

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ABSTRACT

Southwest British Columbia is exposed to earthquakes from the Cascadia Subduction Zone (CSZ), a 1000-kilometer seismic source off the coast of Vancouver Island. The last known CSZ earthquake occurred in 1700, leaving a gap in our understanding of the expected shaking intensity associated with such events. Metro Vancouver's tall buildings, primarily comprised of reinforced concrete shear wall (RCSW) structures, are vulnerable to these earthquakes because the region lies above the Georgia sedimentary basin, which can amplify ground motion shaking, particularly in the medium-to-long period range, and is not accounted for in current building codes. Tall buildings constructed prior to the 1980s are of special concern because they predate modern seismic codes and are clustered in densely populated areas, raising concerns about the risks to life, property, and recovery from large earthquakes.

This presentation addresses these challenges by quantifying the amplification of ground motion shaking due to the Georgia sedimentary basin during CSZ earthquakes, as well as evaluating the expected seismic performance of older tall RCSW buildings. Physics-based ground motion simulations of 30 plausible M9 CSZ earthquakes, which explicitly consider basin effects, are benchmarked against existing ground motion models to develop site-specific and period-dependent basin amplification factors. The presentation also proposes a framework to incorporate these factors into uniform hazard spectra (UHS) calculations, to enable the inclusion of these effects in the design and assessment of buildings.

The collapse risk of older tall RCSW buildings is also assessed via nonlinear response history analysis of 3D numerical models of 25 representative archetypes generated by means of a predictive model that leverages a detailed inventory of such buildings. Collapse risk is quantified using hazard estimates of Canada’s national seismic hazard model, which neglects basin effects, and a “hybrid” hazard model that considers basin amplification. The presentation also showcases the results of a scenario-based seismic performance assessment, under the M9 CSZ earthquakes previously introduced, to quantify economic losses and recovery times in these buildings.

This work intends to address some of the challenges associated conducting regional seismic risk assessments in Southwest British Columbia, and the results aim to inform seismic policy development in the province, in particular, ongoing efforts by the City of Vancouver to address seismic risks in its aging building infrastructure.

Climate change, extreme weather events, and infrastructure resiliency
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE IMPACTS OF HURRICANE DRAG CHANGES ON HURRICANE INTENSITY AND TRACK SIMULATIONS IN WEATHER MODELS

Mostafa Momen[1] and Leo Matak[1]*

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ABSTRACT

Millions of homes and humans in the US are currently at high risk of hurricane destructive forces that can cause billions of dollars in damage. While recent numerical weather prediction models have elucidated many underlying dynamics of hurricane forces, there are still many poorly understood physical mechanisms that can highly impact hurricane simulations [1]. In particular, the dynamical factors that modulate hurricane intensity and track under the surface drag changes are not comprehensively established yet. The main objective of this presentation is to address this knowledge gap by conducting real hurricane simulations using the Weather and Research Forecasting (WRF) model.

To this end, more than 100 WRF simulations of multiple hurricanes are conducted by changing the surface drag values using different planetary boundary layer (PBL) schemes. We will show that the default momentum roughness length (z0) parameterizations in WRF perform well for category 1-2 hurricanes; however, they underestimate the intensities of category 3-5 hurricanes. The default values of z0 in WRF are larger than the observational estimates from dropsonde data in strong hurricanes. Decreasing z0 close to the values of observational estimates and theoretical hurricane intensity models in high wind regimes ($\gtrsim$ 45 m s-1) led to remarkable improvements in the intensity forecasts of strong hurricanes [2].

In terms of hurricane track simulations, our results suggest that the increased surface friction slows down the environmental flow and consequently hurricane track azimuthal translational speed. This finding was confirmed by altering the z0 of the low-wind environmental flow regime. It was demonstrated that the surface drag changes have a similar impact on hurricane tracks as surface temperature variations. Decreasing the default surface drag for low-wind regimes tends to further move the hurricanes toward the west and vice versa [3]. This research provides significant insights into the role of momentum exchange coefficients in hurricane intensity, track, and environmental flow patterns. Furthermore, the results of this work can be useful to advance surface layer and PBL parameterizations of weather/climate models for improved hurricane forecasts.

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Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BONDED DISCRETE ELEMENT METHOD ANALYSIS OF LANDFAST SEA ICE FRACTURE BY OCEAN CURRENTS

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ABSTRACT

Sea ice in the polar regions is subject to a variety of dynamic and thermodynamic processes that determine its yearly permanence. Ocean currents, winds, heat fluxes from the sun, atmosphere and ocean, individual fragment (floe) collisions, and wave action all contribute to the loss of sea ice. Landfast sea ice sheets or fast ice in coastal areas are an example of sea ice that has transitioned from multi-year permanence to a seasonal cycle of formation and collapse. As fast ice plays a vital role in regulating global climate, buttressing glacier shelves, facilitating offshore human activities, and reducing coastal erosion examining its failure process is noteworthy. Failure of sea ice sheets depends on their changing properties and forcing associated to melting and fracturing, particularly at its edges. Loss of sea ice results in enhanced ocean currents and eddy activity, which in turn advance breakage into the sheet and lead to the removal of more ice. This breakdown process can be accelerated by ocean currents and wind, thickness distribution, and thickness reduction induced by melt. In this work, we apply a bonded particle method within the level set discrete element model (LS-DEM-BPM) to explore the relationship between landfast sea ice breakage, ocean currents, and floe size distribution (FSD). First, we consider unidirectional sinusoidal horizontal velocity pulses acting on square and rectangular ice sheets. With these ideal configurations, we isolate the main factors that control breakage. Fracture is found to be conditioned by ocean current wavelength, with a critical cutoff value, and pulse propagation speeds. As a benchmark, we simulate a fast ice region in Fram Strait during 2023 using LS-DEM-BPM and qualitatively reproduce its fracture using ocean current regimes with varying wavelengths (15 and 40 km). The model can approximate in situ breakage FSD evolution using eddying currents with longer wavelengths (40 km). Using LS-DEM-BPM, we can better understand fast ice disintegration and generate various failure events. We identify that the spatial distribution or wavelength of ocean currents significantly affects breakage and FSD characteristics. Diffuse eddies with longer wavelengths (40 km) tend to result in increased fracture area and more uniform FSDs, while concentrated currents of sharp filaments (wavelengths of about 15 km) induce less fracture and produce less smaller floes, for similar kinetic energies. Sea ice sheet thickness reduction below 0.5 m is also associated with a larger failure area and a greater amount of smaller floes.

Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE MODELING OF ELASTOMERIC SEISMIC ISOLATORS

Eduardo Montalto[1] and Dimitrios Konstantinidis[1]*

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ABSTRACT

Elastomeric isolators have been used extensively for the seismic protection of new and existing structures. Extensive research has been done regarding the hysteretic behavior of these devices, and several phenomenological models have been proposed to predict their behavior. The nonlinear geometric effects have also been extensively studied from an experimental perspective, but their numerical implementations have been restricted to simplified models. Today, even the most widely used numerical models for rubber isolators are discrete spring models in which the isolator is treated as a rigid element connected by discrete springs representing their axial, rotational and shear stiffness. The definitions of these springs are manipulated analytically such that the model captures fundamental behaviors such as the buckling of the isolators. This approach presents drawbacks for capturing some behaviors of the isolators, such as accurately predicting the local stresses which are important in predicting the cavitation under tensile stress (or detachment in the case of unbonded elastomeric isolators), as well as incorporating the response for non-standard boundary conditions such as supports under rotations. In this study, a fully mechanical multiscale model for elastomeric isolators is proposed that considers the continuous deformations in the isolator while also accounting for the periodic microstructure formed by the alternating rubber and reinforcement layers. At the macroscale, the isolator is treated as a one-dimensional continuous Cosserat rod which allows for finite deformations. At the microscale, a unit cell formed by a single rubber layer and two half-thickness reinforcement layers is analyzed using finite element simulations; different alternatives with varying levels of complexity, computational cost and accuracy are evaluated for the analysis of the microscale response. The proposed model is compared against high-fidelity finite element simulations and results from previous experimental programs, showing promising results.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WARPING EFFECTS ON THE STABILITY OF SHEAR-FLEXIBLE STRUCTURAL MEMBERS

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ABSTRACT

Slender structural elements such as beams are vulnerable to buckling phenomena when subjected to compressive loads. The slenderness of these bodies usually allows to model them following the Kirchhoff assumption that plane sections remain plane and orthogonal to the deformed axis of the element. Elements which are very flexible in shear, such as composite sandwich panels or rubber bearings, exhibit a different behavior and buckling can occur for non-slender elements rendering the Kirchhoff assumption invalid. Two main theories have been developed for the buckling of shear-flexible beams, namely Engesser's and Haringx's theories. These theories have proven to be effective for different structural applications, but yield vastly different estimations of the bifurcation loads. Although both theories assume that cross sections remain plane, they adopt distinct assumptions regarding the line of action of the compressive load. From a continuum mechanics perspective, it has been argued that the different lines of action of the axial loads at a structural element level originate because the theories assume material linearity with respect to different finite strain measures. Overall, these differences have been the source of extensive controversy and discussion over the last 50 years. In this study, it is argued that the line of action of the compressive load is not arbitrary nor determined by the material constitutive theory, but rather depends on the shear-warping flexibility of the structural member. A beam buckling theory that accounts for the cross-sectional distortions due to shear recently developed by the authors within the context of the stability evaluation of rubber bearings with flexible reinforcement is shown to unify the treatment of Engesser and Haringx. The seemingly disjoint assumptions of these formulations are shown not to be in disagreement. Instead, they correspond to the extreme cases of elements that are fully flexible and fully rigid in warping. The analytical results of the proposed formulation are validated using high-fidelity finite element simulations for a wide variety of shear-flexible structural members.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENFORCING COUPLING OF SMART HABITAT SUBSYSTEM MODELS WITHIN A SYSTEMS-OF-SYSTEMS MODELING FRAMEWORK

Adnan Shahriar[1], Arsalan Majlesi[1], David Avila[1], Herta Montoya[2] and Arturo Montoya[1]*

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ABSTRACT

Ensuring the efficient execution of system-of-systems (SoS) frameworks relies on modularity, demanding both managerial and operational independence among constituent systems. This research investigates the feasibility of establishing displacement compatibility between two interconnected yet independent finite element (FE) models in solid mechanics, linked by a contact interface within an SoS. The approach proposed addresses this by solving each system independently, using displacement and pressure inputs from the coupled model. Operational independence is maintained by delaying displacement compatibility in one system, which then provides a trial displacement input to the leading system. The leading system assesses the error discrepancy between both systems, utilizing it to calculate an equivalent pressure that enforces displacement compatibility. The effectiveness of this method was validated by modeling two specimens with a frictionless contact interface and comparing the results against a continuous model assuming a perfect bond between the specimens. Finally, the method was implemented within an SoS for space habitats, demonstrating its efficacy in ensuring matching displacement at the contact surface between two interacting structural layers. Importantly, the proposed approach maintains the modularity of coupled systems, eliminating the need for complex iterative procedures and the transfer of mass and stiffness information between different systems.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMOMECHANICAL REAL-TIME HYBRID SIMULATION FOR LUNAR HABITATS

Herta Montoya[1], Manuel Salmeron[1], Christian Silva[1] and Shirley Dyke[1]*

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ABSTRACT

Thermomechanical real-time hybrid simulation (RTHS) enables the two-way thermal coupling between a numerical and an experimental subsystem, expanding the range of hybrid simulation methods to study thermal effects on systems. The interactions between the numerical model and the physical specimen occur through a novel thermal transfer system that imposes distributed cooling (or heating) thermal loads on the physical specimen. This study demonstrates the experimental thermomechanical RTHS implementation to examine the thermal response of a conceptual Lunar habitat system consisting of a pressurized two-layered composite structural system made of Lunar regolith and aluminum. The habitat interacts with the external Lunar environment, including extreme environmental conditions and hazards such as meteorite impact. Examining the thermal response of a pressurized two-layered composite structural system made of Lunar regolith and aluminum is not experimentally reproducible in a laboratory, and analogous geological environments are not easily accessible. Thus, thermomechanical RTHS allows us to simulate the Lunar regolith and environment numerically while physically testing the aluminum pressurized structure and enforcing subsystem interactions. This pioneering approach to execute multi-physics RTHS testing is illustrated by a scenario that includes structural damage and cascading thermal effects for the Lunar habitat.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPERATOR LEARNING VIA NEURAL NETWORKS WITH KERNEL-WEIGHTED CORRECTIVE RESIDUALS

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ABSTRACT

Over the past few years, a novel class of methods known as physics-informed machine learning (PIML) has emerged as a promising alternative to traditional numerical methods for solving partial differential equations (PDEs). These PIML models typically rely on variants of neural networks (NNs) or kernel methods such as Gaussian Processes (GPs). In this presentation, we introduce NNs with kernel-weighted corrective residuals (CoRes) which integrate the best of both worlds: the scalability and extrapolation power of NNs with the superior local generalization properties of kernel methods close to the boundaries. We demonstrate that our approach can (1) exactly satisfy the prescribed boundary and initial conditions, thereby simplifying the optimization process, (2) address inverse problems by incorporating additional measurements in the kernel structure, and (3) solve operator learning tasks. Through a diverse set of benchmarks, we show that our framework consistently outperforms state-of-the-art PIML methods in terms of accuracy, robustness and development time.

BAYESIAN NEURAL NETWORKS FOR ACTIVE LEARNING AND UNCERTAINTY QUANTIFICATION WITH BIG DATA

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ABSTRACT

The performance of engineering systems can be effectively quantified through computational models, information retrieved from inspections, or a combination thereof. However, acquiring information through high-fidelity simulations and inspection campaigns often entails considerable expenses. In this context, active learning strategies serve as a suitable method for collecting new data based on uncertainty estimates computed by a predictive model. Within the structural reliability domain, surrogate models trained via active learning have been thoroughly investigated. In most studies, the reliability is estimated through Gaussian process-based surrogate models, owing to their capacity to capture uncertainty in model predictions. However, their use in medium- to high-dimensional and large-scale data applications is limited by computational constraints. From a slightly different perspective, active learning approaches have also been investigated by the machine learning community. Theoretically, Bayesian neural networks (BNNs) offer a solid framework for probabilistic inference, enabling data labeling via a customized acquisition function based on uncertainty metrics. However, major simplifications are often imposed in practical applications to cope with the otherwise intractable Bayesian inference problem.

In this work, we investigate the effectiveness of active learning strategies when combined with BNNs, especially in scenarios where experiments or data collection efforts are limited or costly. Specifically, we formulate and test state-of-the-art BNN variants such as (i) mean-field variational inference; (ii) stochastic gradient Hamiltonian Monte Carlo; and (iii) Monte Carlo dropout. We subsequently examine the performance of acquisition functions to strike a balance between exploration and exploitation in active learning. Through two comprehensive case studies, we showcase the capabilities of BNN-based active learning methods and compare them against ensembles of neural networks. The first study involves estimating the structural reliability of a 100-random variable engineering model, analyzing the failure probability evolution over the number of active points. In the second case study, we apply the method in a big data context, framing building energy auditing as an active learning problem to estimate the energy efficiency of 15,000 buildings through machine vision. A vector of embeddings is generated via the DINOV2 foundation model for each building's aerial image, and subsequently, the embeddings are used to predict buildings' energy efficiency category through BNNs. In each active learning step, the selected input-label pairs are added to the training set, the BNN models are retrained, and the validation error is monitored. The results indicate that BNN-based active learning approaches are capable of effectively handling large-scale problems, managing complexity and uncertainty in diverse environments.

UNDERSTANDING MULTI-AGENT COOPERATION IN DEEP REINFORCEMENT LEARNING FOR INSPECTION AND MAINTENANCE PLANNING

Prateek Bhustali[1], Charalampos Andriotis[1], Pablo G. Morato[1] and Kostas Papakonstantinou[2]*

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[2]The Pennsylvania State University

ABSTRACT

Inspection and maintenance (I&M) planning for deteriorating engineering systems is essential to maximizing the utility we derive from them. This sequential decision-making problem can be formulated as a partially observable Markov decision process (POMDP), which mathematically captures the stochastic state degradation and partial observability of the controlled environment. Theoretically, this can be solved through single-agent deep reinforcement learning. However, single-agent approaches scale poorly for multi-component systems as the joint state, action, and observation spaces grow exponentially with the number of components. Decentralized POMDPs (Dec-POMDPs) relax the assumption of joint spaces, offering an elegant alternative that enables scalability through decentralization of observations and actions. Dec-POMDPs can be readily solved through multi-agent deep reinforcement learning (MADRL) algorithms [1]. Based on information available during training and execution, MADRL algorithms can be classified into three paradigms: (i) centralized training with centralized execution (CTCE), (ii) centralized training with decentralized execution (CTDE), and (iii) decentralized training with decentralized execution (DTDE). Similar to [2], we systematically evaluate these three paradigms in this work in the context of I&M planning using two common archetypes of deteriorating engineering systems: k-out-of-n and series-parallel systems. We focus specifically on understanding the characteristics of the learned joint policy, learning stability, effect of parameter sharing and cooperation dynamics of the agents under varying decentralization relaxations in such systems. Additionally, we establish baseline solutions, also using point-based POMDP solvers when feasible, offering global optimality guarantees, to serve as appropriate comparative metrics.

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Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HUMAN-MACHINE-STRUCTURES INTERFACES ENABLING NEW THEORIES FOR MANAGEMENT AND SAFETY

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[1]University of New Mexico

ABSTRACT

We are experiencing a nationwide infrastructure crisis and new solutions to enable safer, cost-efficient and reliable management methods are needed. At the same time, in recent decades, infrastructure aging, new social behavior, urban and rural environmental changes, and nature or human made extreme events have increased in complexity. Owners and stakeholders demand higher quality and details from structural inspections. The concept of Digital Twin (DT) opens a possibility of bi-directional interaction between data, infrastructure, and humans, but to date it has not been exploited in the field on real-time. If users, first responders, managers, or planers would be able to access structural data in the field directly, they could transform decisions in real-time (in the laboratory, the machine shop, or the field). This presentation summarizes ongoing work on infrastructure design and maintenance decisions exploring the concept of human-structure interfaces associated with machines. The interfaces are achieved with Augmented Reality (AR). The presentation summarizes work in human-in-the-loop with application on near real-time computer vision, robot enabled access to structural inspections, and new approaches to real-time control of operations that transform the human-machine-structure interfaces paradigm in civil engineering.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-ELEMENT PSEUDO-DYNAMIC HYBRID SIMULATIONS ON HIGH-PERFORMANCE DUCTILE STEEL STRUCTURES AT THE UNIVERSITY OF TORONTO

Pedram Mortazavi[1], Oh-Sung Kwon[2] and Constantin Christopoulos[2]*

[1]*University of Minnesota*
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ABSTRACT

Substructuring pseudo-dynamic hybrid simulation is an efficient and effective testing method for understanding the system-level response of structures which are subjected to extreme loading scenarios with a random loading history. In pseudo-dynamic hybrid simulation, the critical structural components which predominantly affect the response are tested physically, while the remaining structural components are modelled numerically. The former is referred to as the physical substructure, while the latter is referred to as the integration module. In hybrid simulation, the response of the physical substructure is integrated into the response of the integration module, by forming a communication framework between the two. In the last few decades, pseudo-dynamic hybrid simulation methods have undergone significant advancements, and the method has been widely used for performance assessment of different structural systems. However, one of the main shortcomings of pseudo-dynamic hybrid simulation is the limited number of physical substructures that can be tested in each hybrid simulation, due to limited laboratory resources and the complexity of adding additional physical substructures. The University of Toronto Ten Element Hybrid Simulation Platform (UT10) was recently developed, in order to push the boundaries with the number of physical substructures that can be tested in pseudo-dynamic hybrid simulations. The UT10 is designed to test up to ten uniaxial rate-independent physical substructures simultaneously. So far, the UT10 has been used for performing multi-element pseudo-dynamic hybrid simulations on several high-performance ductile steel structures including buckling restrained braced frames, special concentrically braced frames, yielding brace systems with cast steel yielding connectors, and more recently, a controlled rocking steel structure. This presentation provides a brief overview of the UT10 and its features. Selected past multi-element hybrid simulations using the UT10 are presented. The challenges, lessons learned, and findings from each multi-element hybrid simulations are presented. In the end, visions for future research projects using multi-element hybrid simulation are presented.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCED AEROCAPTURE SYSTEM FOR CONTROLLING SPACECRAFT DURING HYPERSONIC ENTRIES AT WORLDS WITH ATMOSPHERES

Robert Moses[12]*

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[2]Tamer Space, LLC

ABSTRACT

Researchers at NASA’s Langley Research Center have designed an electrode-based system for guidance, navigation and control of aircraft or spacecraft moving at hypersonic speeds in ionizing atmospheres. The system is composed of two electrodes that sit on the surface of a craft’s thermal protection system (TPS) and an electromagnet positioned beneath the craft’s TPS. The system operates based on the principles of magnetohydrodynamics (MHD) and uses energy harvested from the ionized flow occurring during flight at hypersonic speeds to power the electromagnet and generate extremely large Lorentz forces capable of augmenting lift and drag forces to steer and control the craft. The energy harvested can alternatively be stored for later use. NASA’s system is simpler than conventional methods for control of hypersonic craft (e.g., chemical propulsion, shifting flight center of gravity, or trim tabs) and enables new entry, descent, and landing mission architectures. NASA’s MHD patch technology consists of two electrodes positioned a prescribed distance apart on the surface of the TPS of an aircraft or spacecraft and an electromagnetic coil placed directly below the electrodes with the magnetic field protruding out of the surface. During hypersonic flight, the conductive ionizing atmospheric flow over the surface enables current to flow between the two electrodes. This current is harnessed to power the electromagnet which in turn generates strong Lorentz forces that augment lift and drag forces for guidance, navigation, and control of the craft. Alternatively, the current can be used to charge a battery. Changing the size of the MHD patch (e.g., the length or distance between the electrodes), the strength of the electromagnet, or the direction of the magnetic field enables tuning of generated forces for a given craft design. Multiple MHD patches can be leveraged on a single craft. In-silico evaluation of the MHD patch technology on select aeroshell designs for mock entry into planetary atmospheres has been performed. A 1m2 MHD patch exerts forces up to 200 kN under simulated Neptune atmosphere entry, significantly increasing the lift/drag (L/D) ratio for the aeroshell investigated. This value is the same order of magnitude as the “whole body” drag and lift forces computed for the aeroshell suggesting the generated forces can be used to control a craft. This concept generates steering and drag forces much higher in the atmosphere than possible aerodynamically. Because the spacecraft does not need to enter the atmosphere as deeply as other concepts, the thermal loads on the TPS are reduced by as much as 70%. This concept enables new mission classes to worlds with atmospheres as well as fast return missions to Earth from the Moon or Mars.

Keywords: aerocapture; magnetohydrodynamic; hypersonic flight; power generation; planetary missions; guidance, navigation, and control; autonomous flight operations; atmospheric entry.

Reference: “System for Flight Control of Extremely Fast (Hypersonic) Aircraft : Lift-augmenting, power-harvesting magnetohydrodynamic patch," https://technology.nasa.gov/patent/LAR-TOPS-363, https://ntts-prod.s3.amazonaws.com/t2p/prod/t2media/tops/pdf/LAR-TOPS-363.pdf

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIERARCHICAL BAYESIAN MODEL UPDATING OF A 6 MW OFFSHORE WIND TURBINE FOR UNCERTAINTY QUANTIFICATION WITH COMPARISON TO A FREQUENTIST APPROACH

Bridget Moynihan[1], Babak Moaveni[1] and Eric Hines[1]*

[1]Tufts University

ABSTRACT

The structural reliability of offshore wind turbines is vital to ensuring the reliability and safety of clean energy resources. To monitor offshore wind turbines, instrumentation campaigns are used to measure the vibrational response of such large infrastructure. These measurements can then be used in the development of a digital twin¬—a virtual model which closely matches the true structure—typically by matching the modal parameters of the model to those identified from the measured response. Digital twins can be used to predict the dynamic response of the structure due to loading conditions, to predict breakages, or to estimate the remaining useful lifetime. In the process of digital twinning, model updating is carried out on an initial virtual model to bring it into close agreement with the true structure. This paper performs finite element model updating of an operational 6 MW offshore wind turbine using two methods – a hierarchical Bayesian inference and a frequentist approach where a probability distribution is fit to the histogram of deterministic model updating results. The turbine is monopile-supported and instrumented with strain gauges and accelerometers at several elevations along the tower and monopile. The simplified model implements a spring stiffness at the hub height of the turbine to simulate aerodynamic stiffening. Optimal hub-level spring values are estimated in the model updating framework based on operational and environmental conditions. Model updating is performed through a hierarchical Bayesian framework in order to estimate the parameter uncertainty and to capture the inherent variability in the structural parameters with ambient conditions such as wind speed. Results of this approach are then compared to the distribution of the deterministic model updating results using several windows of 10-minute measurements. Each approach is intended to provide a probabilistic estimate for the hub-level stiffness at varying operational conditions which can inform the use of the digital twin. The model updating framework is carried out on data from a 2-week period of operational, power-producing, conditions.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PHASE-FIELD FORMULATION FOR FRACTURE MODELING OF RATE- AND TEMPERATURE-DEPENDENT MATERIALS

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ABSTRACT

The phase-field method is gaining recognition as a powerful numerical tool in computational fracture mechanics due to its ability to model crack nucleation, propagation, branching, and coalescence. Recently, we recast the Park-Paulino-Roesler (PPR) cohesive zone model within the phase-field modeling framework, resulting in the creation of a new model called the regularized PPR model. This new phase-field model facilitates the simulation of fracture in a broad range of materials characterized by either convex, linear, or concave softening responses. The regularized PPR model, which was initially designed for rate- and temperature-independent materials, faces limitations when applied to materials such as asphalt or polymers, known for their temperature-dependent viscoelastic behavior. To overcome this limitation, we extended the regularized PPR model to account for thermoviscoelasticity. Specifically, we consider a weakly coupled thermoviscoelastic problem tailored to isotropic linear viscoelastic media and solve for the effective stresses via an incremental approach, such that the stresses at the current time step can be computed recursively based on the stresses at the previous time step. To model nucleation and evolution of cracks, we consider a driving force defined in terms of the elastic and viscous energies in the bulk. In this presentation, we will discuss the derivation of the new thermoviscoelastic phase-field model and will discuss several numerical examples to show the ability of the model to simulate complex crack topologies for structures subjected to complex thermomechanical loads.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF A COMPUTATIONALLY EFFICIENT LARGE-SCALE THREE-DIMENSIONAL MODEL FOR FRACTURE PROPAGATION USING PARALLEL COMPUTING AND ADAPTIVE MESH REFINEMENT.

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ABSTRACT

Detection and tracking of cracks are important in engineering analysis and design. Despite numerous developments in high-fidelity finite element models over the years, a reliable three-dimensional fracture simulator remains elusive. Many existing models are limited to two dimensions, cannot simulate non-planar failure surfaces, and complex crack interactions like branching and coalescence. Therefore, it is essential to devise a method capable of capturing the behavior of closely interacting cracks in three dimensions (3D) for accurately predicting the failure behavior of engineering materials.

In recent years, the phase-field method has gained popularity for modeling brittle fractures due to its ability to seamlessly handle complex crack interactions. This method considers damage as a smeared zone in the continuum with degraded mechanical stiffness. Damage, along with displacements, is solved as a nodal field, eliminating the need for explicit crack tracking. Fracture propagation is treated as an energy minimization problem, eliminating the need for additional crack propagation criteria. However, the computational expense of accurately resolving the smeared zone of damage remains a challenge. The phase-field method requires very fine meshes in the smeared zone to capture the sharp gradient in the damage field. For real-life engineering problems, the crack path is not known apriori and, therefore, a fine mesh is required throughout the domain. While attempts have been made to reduce this computational burden through mesh adaptivity [1], applying the phase-field approach to fully three-dimensional problems is still limited due to its high computational cost.

This study aims to develop a large-scale three-dimensional phase-field framework for simulating fracture propagation under purely mechanical loading. The phase-field method is implemented in deal.II, a C++ finite element library. deal.II is known for its better performance in computational cost and memory management, making it suitable for large-scale problems [2]. We employ the advanced computational capabilities of deal.II, such as parallel computing and adaptive mesh refinement, to offset the high computational cost. After that, we present the results from several numerical experiments to investigate the influence of relative fracture orientations, fracture interactions and mismatch in mechanical properties on fracture propagation in both homogenous and heterogeneous material systems.

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Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATION OF PHYSICS-INFORMED MACHINE LEARNING FOR REDUCED DATA SHEAR PREDICTION

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ABSTRACT

The field of civil engineering is witnessing a growing integration of machine learning algorithms and techniques into standard practices. Conventionally, the efficacy of machine learning hinges upon the availability of substantial and domain-relevant data, without which it is difficult to generate models that deliver precise predictions. Unlike several other disciplines, civil engineering faces a scarcity of pertinent data across various domains, a condition particularly accentuated in the discipline of structural engineering. To address the challenge of limited data availability in structural engineering, the potential of relational transfer learning and physics-informed machine learning will be explored. The focus will be on predicting shear strength in beams and columns, two critical components in structural engineering.

Transfer learning (TL) is a machine learning technique that utilizes existing data in an adjacent domain to improve the model on the desired target domain. The goal is to transfer knowledge from a source domain to the target domain without negatively affecting learning on the target data. Relational transfer learning is a method of TL that transfers knowledge in the form of relationships between features in the source dataset to the target dataset.

Physics-informed machine learning seeks to embed domain-specific physical laws and constraints into machine learning models, thereby enriching predictive capabilities, and ensuring the generated solutions adhere to underlying scientific principles. This method has significant promise, especially in fields where traditional machine learning models encounter challenges due to limited data availability or when explicit physical insights can enhance the reliability of predictions.

To determine the benefits of physics-informed machine learning in this application, there will be four models evaluated: a baseline machine learning model, a transfer learning model, a physics-informed model, and a joint physics-informed and transfer learning model. The performances of these models for differing levels of data availability and on different directions of transfer will be presented and discussed. By leveraging these advanced methodologies, the research endeavors to enhance predictive capabilities in the absence of an abundance of data, thus contributing to the broader integration of machine learning in civil engineering practices.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MESOSCALE MODELING OF ULTRA-HIGH PERFORMANCE CONCRETE WITH RANDOMLY DISTRIBUTED STEEL FIBERS

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ABSTRACT

Due to its outstanding mechanical properties and durability, ultra-high-performance fiber-reinforced concrete (UHPFRC) has attracted significant attention as a composite material influencing the future of civil infrastructure. Despite some successful applications of UHPFRC, its structural use remains limited, primarily due to a lack of understanding of its mechanical behavior. The discrete modeling of individual fibers in cement-based materials has been proven to have several advantages, including the ability to simulate the pre- and post-cracking composite performance. Here, a mesoscale model for UHPFRC is developed to model the response of UHPC under different loading conditions accounting for the matrix, fiber inclusions, and their imperfect interfaces. This work proposes a mesoscale finite element framework with zero thickness interface enrichment to model the homogenized response of UHPFRC under generalized loading conditions. The model accounts for two phases of the composite material, the linear elastic UHPC matrix, the elastoplastic steel fibers, and the imperfect cohesive interface. The fibers are randomly distributed and oriented. The developed framework will be validated through well-thought-out experiments, probing individual constituents and their interactions, such as fiber-matrix pull-out test and microstructural imaging. The accuracy of the proposed model will also be tested using the data in the literature, including uniaxial compression, direct tension, and three-point bending. The developed framework forms the computational foundation to help understand the collective behavior of discrete constituents on the overall behavior of UHPFRC and suggest improvements in practical applications.

EVALUATING ACCURACY IN RESPONSE PREDICTION OF NONLINEAR SYSTEMS

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ABSTRACT

In engineering, problems and applications often involve uncertainty and accurately assessing the potential effects of these uncertainties is crucial. The conventional approach to do this is probabilistic simulation, but it may become impractical for complex problems. Selecting a small-to-moderate number of samples to represent the entire set of scenarios is a challenging open problem. While researchers primarily aim to enhance the representation of system inputs (e.g., structural loads) for improved response prediction, a deeper investigation is necessary when dealing with intricate filters that complicate the prediction of response accuracy. One method to perform this selection of inputs is a technique called "Functional Quantization by Infinite Dimensional Centroidal Voronoi Tessellation (FQ-IDCVT)", which is based on mean-square optimality and reduces sample variability. To address this, various methods for sample selection are proposed to capture the extremities of the distribution and other probabilistic characteristics. Despite promising results in enhancing probabilistic properties, achieving a robust representation of probabilistic response behavior remains challenging. Complex transformations between inputs and outputs, especially in the presence of complex filters, contribute to this complexity. Complex filters can introduce nonlinearities, interactions, and amplification effects, making it more difficult to establish a direct link between input probabilities and output behavior. This shows the importance of comprehensive modeling and analysis of the entire input-output transformation process. To leverage our knowledge of the filter (e.g., a structure) for enhancing the representation of the output, here we propose defining importance factors based on the system and output quantities of interest. To illustrate this framework, we applied it to a nonlinear multi-degree of freedom structure.

MULTI-FIDELITY SUBSET SIMULATION FOR RARE EVENT SIMULATION

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ABSTRACT

Subset Simulation (SS) is an efficient method used for simulating rare event and estimating small probabilities, particularly in the field of structural reliability analysis. The original SS is developed for system with single fidelity model. While for many systems, besides high-fidelity model, typically lower-fidelity models can be developed that are less expensive albeit with lower accuracy (compared to the high-fidelity model). In this work, a novel multi-fidelity subset simulation (MFSS) approach is proposed that extends the single fidelity SS to the more general multi-fidelity SS by leveraging the high accuracy of the high-fidelity model and the high efficiency of lower-fidelity models to improve the overall efficiency of SS. The proposed approach relies on formulation of an augmented failure probability problem by artificially treating the model fidelity as a discrete random variable and augmenting it with other random variables/inputs. Further, Bayes' theorem is used, to estimate the probability of failure for highest fidelity model using information from subset simulation for the augmented failure problem. Since density estimation requires independent and identically distributed (i.i.d.) samples, instead of using Markov Chain Monte Carlo (MCMC) that is typically used in SS, at each level of MFSS modified rejection sampling algorithm with adaptive kernel sampling density (AKSD) is used to efficiently generate i.i.d. failure samples. At each MFSS level, an optimization problem is formulated to optimally allocate the computational efforts for each model fidelity to minimize the cost needed to generate the required number of samples. The proposed method requires only a small number of runs of the high-fidelity model and a larger number of runs of lower fidelity models, which results in a smaller computational cost compared to when using subset simulation with only high-fidelity model. The accuracy and computational savings offered by the proposed approach are comprehensively investigated using two benchmark problems.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS-INFORMED NEURAL OPERATOR NETWORK: ACOUSTIC SIMULATIONS OF ARBITRARY-SHAPE SCATTERERS

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ABSTRACT

Computational methods for the design of architected materials are in high demand due to the complexity and vastness of the design space. Classical inverse methods based on iterative approaches are severely limited by the computational time associated with the evaluation of the forward model. Reducing the computational time for the forward model significantly impacts performance as multiple forward evaluations are required in the iterative process to estimate the physical response of the system. Finite element (FE) methods are a popular choice for the solution of a wide range of mechanical problems, however, their intrinsic mesh-dependence and the heavy computational cost associated with every change of parameters (due to the need to re-evaluate the inverse of large matrices) limit significantly the overall performance of the inverse method.

In recent years, deep learning has emerged as a powerful tool to solve both forward and inverse problems in engineering. While data-driven methods are heavily dependent on large training databases and produce physically inconsistent approximations, physics-driven methods like physics-informed neural networks (PINNs) are capable of generating physically-consistent predictions without relying on labeled training data. PINNs introduce a learning bias by enforcing the governing physics through appropriate loss functions and constraints. However, similar to FE-based forward solvers, the PINNs also incur significant computational cost due to their need to repeat the training for individual computational domains.

We present a physics-informed deep operator network (DeepONet) model capable of handling computational domains with different geometries without requiring a new training. The effectiveness of this operator learning model is illustrated by its application to rigid body acoustic scattering. The proposed network integrates the concept of NURBS-based geometry parameterization to represent the scatterer geometries. This approach improves the generalization performance as it allows approximating the solution for computational domains embedded with NURBS-based scatterer geometry of arbitrary shape and size. In addition, the proposed network is capable of simulating the problem without relying on any labeled training dataset, but instead by enforcing the underlying physics through the governing partial differential equations. Moreover, in contrast to FE and PINN, which require repeated evaluations of each independent scatterer shape, the trained DeepONet can speed up the scattering simulations involving arbitrary-shaped scatterers because it requires only a single initial training. The prediction accuracy and computational time of the proposed network are compared with those obtained from a commercial finite element software model to assess the performance of the method.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRESS-CONSTRAINED DESIGN OF HIERARCHICAL STRUCTURES USING SECOND-ORDER HOMOGENIZATION AND MACHINE LEARNING

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ABSTRACT

Multiscale structural optimization considers the simultaneous design of both the macroscale (observable) structure and its microscale constituents. In this work, spatially varying microarchitectures control local structural properties. Driven by advancements in additive manufacturing, this introduction of complicated microarchitectures in the microscale design space can produce superior structures for high strength-to-weight and energy absorption applications. Numerical homogenization techniques have traditionally been used to incorporate microarchitecture mechanics through the evaluation of their effective mechanical properties. This approach, however, fails to capture microstructure-level phenomena such as local stress concentrations. The deliberate integration of these microarchitectures into the greater structure must also include both microscale and macroscale design variables. To address these challenges, numerical homogenization is used to estimate the local response of the microarchitecture, while design parameterization is used to limit the multiscale design space.

This presentation seeks to extend the homogenization approach to design optimization using machine learning. As in traditional topology optimization, we implement a surrogate for parameterized homogenization to model the micro-to-macro transition. As a surrogate, we explore the deep neural network (DNN) for its ability to efficiently model high-dimensional and nonlinear functions for stress amplification in each microarchitecture. In addition, we tune the DNN’s training dataset using finite element simulations of second-order numerical homogenization. The second-order homogenization method incorporates a strain gradient into the microstructural analysis, increasing the information exchange between the macro- and microscales and addressing problems of scale separation. The model is applied to evaluate the local stress amplification caused by spatially varying microarchitectures. Through numerous examples, we show how a model can be used to efficiently evaluate hierarchical structures in stress-constrained design.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCING REAL-TIME HYBRID SIMULATION: COMPLEXITIES AND INNOVATIONS IN BOUNDARY CONDITIONS

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ABSTRACT

Real-time hybrid simulation, a technique that has become prominent since the 1990s, effectively merges the fidelity of physical testing and versatility of computational methods and is able to accurately represent the actual speeds at which natural forces and excitations occur. A key focus in advancing Real-Time Hybrid Simulation (RTHS) technology has been the exploration of more complex boundary conditions, which serve as the interface between the physical and computational components of the models. Enhanced boundary conditions in this context involve the integration of multiple actuators collaborating to apply complex kinematic movements, alongside sensors whose data can be combined to yield more accurate and comprehensive measurements. This presentation delves into the various complexities, including those related to testing, modeling, and algorithms, that are encountered in the development of an RTHS system with 12 degrees of freedom for a modeling of a multi-span curved bridge structure. Lessons learned in areas such as numerical integration schemes, actuator compensation, and kinematic transformation are discussed.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHASE-FIELD COHESIVE ZONE CRACK PROPAGATION MODEL FOR HARD-SOFT ARCHITECTED MATERIALS

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ABSTRACT

Recent advancements in architected materials have shown promising applications across various industrial domains such as civil, aerospace, and biomedical engineering. Architected multi-materials, such as hard-soft assemblies with tunable properties, can be realized given the advancement in additive manufacturing techniques. These materials exhibit complex failure mechanisms, such as crack deflection, penetration, and bridging, due to the often heterogeneous or non-uniform arrangement of materials of different constitutive properties. These mechanisms are crucial in determining key bulk characteristics like fracture toughness and strength in these composite materials. One important challenge in capturing fracture behavior in soft-hard assemblies is the existence of interface regions that require special considerations in numerical simulation. To address this challenge, we present a numerically robust constitutive framework for modeling fracture behavior in architected materials composed of alternating soft elastomers and hard cement paste in bilayer assemblies. The framework utilizes the phase-field approach to capture crack propagation within the bulk of the hyperplastic soft and elastic hard materials. Furthermore, to understand the contribution of the interface to the fracture energy potential, the constitutive relationships are further supplemented with a Cohesive Zone Model (CZM). Through a series of parametric evaluations, we demonstrate that our coupled phase-field CZM framework allows for the prediction of complex cracking phenomena in architected multi-materials (e.g., deflection, penetration, bridging). Furthermore, we illustrate the effectiveness of the proposed framework in capturing the toughening mechanisms anticipated in soft-hard assemblies enabled through intelligent design of such materials architecture and advanced additive manufacturing processes.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROGRESSIVE WRINKLING AND COLLAPSE OF LINED PIPE DUE TO REPEATED WINDING/UNWINDING ON REEL

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ABSTRACT

Carbon steel tubes and pipe used in power plant and pipeline applications are often protected from corrosive contents by lining them internally with a thin layer of a corrosion resistant alloy (CRA). The liner is installed by mechanically expanding it inside the carbon steel tube so that they end up in contact. In the process the liner acquires the imperfect shape and relief of the inner surface of the carrier pipe. Under plastic bending, the liner can detach from the carrier pipe and develop large amplitude wrinkles and local buckles rendering the structure unserviceable [1]. The presented work investigates how repeated winding and unwinding of a lined pipe on to a large diameter reel, leads to progressive accumulation of wrinkling, and eventually collapse of the liner.

The reeling/unreeling process in the presence of small amount of back tension is modeled via a large scale finite element analysis [2]. Small amplitude geometric imperfections introduced to the liner/carbon steel interface during the manufacture are included in the analysis. The stress-strain response of both the carbon steel carrier and the CRA under axial cycling are measured experimentally. The responses are used to calibrate a nonlinear kinematic hardening constitutive model capable of simulating accurately the Bauschinger rounding of reverse loading. Simulations of repeated reeling/unreeling demonstrate that the resultant plastic bending leads to small amplitude wrinkles to the liner. The wrinkle amplitude progressively grows with each cycle, eventually causing it to collapse. The rate of accumulation of wrinkle amplitude with the number of applied cycles and the number of cycles to collapse are studied parametrically. It is demonstrated that the number of cycles to collapse is strongly dependent on the amplitude of the initial geometric imperfections. This sensitivity is reduced if a modest amount of internal pressure is added to the pipe during winding/unwinding and delays collapse.

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Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATIONAL SIMULATION OF TORNADO DAMAGE AND RESPONSE FOR HISTORICAL MASONRY BUILDINGS FROM FIELD RECONNAISSANCE DATA

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ABSTRACT

While there is a great deal of research being done at the intersection of extreme wind loading and structural strengthening, the implications for historic and aging infrastructure, are often neglected. Notably, the ASCE 7-22 standard currently excludes Risk Category I and II structures, which encompass a substantial percentage of historic structures and get impacted during tornadic activity. This research focuses on the historic masonry structures located in Mayfield, Kentucky, that were impacted by the Midwest Tornado Outbreak in December 2021. To understand the implications of tornado loads on historic masonry, the damaged buildings were digitally documented using an array of techniques such as LiDARs, Unmanned Aerial Vehicles, and Street View cameras. The point clouds generated via these documentation techniques were converted to finite element models, for evaluating the structural response under two different loading conditions. The first loading conditions were estimated using the wind speeds prescribed in the ASCE 7-22 standard, while the second were estimated wind speeds derived from the disaster site. Initially, a sensitivity analysis was performed in ABAQUS to estimate the material properties of the damaged structures. This was followed by a nonlinear analysis under the predefined loading conditions. Through this investigation, it became evident that the application of on-site wind speed data resulted in stress distributions and damage patterns that were significantly higher than those derived from the ASCE 7-22 standard wind speeds. These disparities have notable implications for the assessment of structural vulnerabilities and post-hazard strengthening efforts in historical buildings. The outcomes of the study emphasize the need for additional research to enhance the resilience of historic buildings to extreme wind events, particularly for structures that fall under RC I and II, which the current design code and standards do not cover. Further efforts are necessary to improve the comprehension of the impact of extreme wind events on historical buildings and to establish effective strategies for strengthening these structures to mitigate the impact caused by natural hazards.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FULLY AUTONOMOUS BRIDGE VISUAL INSPECTION BASED ON MOBILE ROBOTS WITH VISUAL RECOGNITION CAPABILITIES: TECHNICAL ROADMAP AND PROTOTYPE DEVELOPMENT

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ABSTRACT

This research discusses the technical roadmap and prototype development for replacing the human inspectors for bridge visual inspection by autonomous mobile robots. The envisioned mobile robotic system first navigates and collects high-quality image data of critical structural components based on its own visual recognition of the bridge inspection scenes. The collected data is further post-processed to provide information about structural conditions. Preliminary results in structural component recognition, navigation planning, and data post-processing steps are presented. Then, ongoing work to integrate those subsystems into a prototype autonomous system in the laboratory environment is discussed. Finally, the challenges that need to be addressed to realize such a complex autonomous system that performs tasks in the field environment are discussed. This work will motivate further investigations to accelerate the ongoing transformation in autonomous structural inspection.

EFFICIENT COMPUTATION OF REDUCED ORDER BASIS FOR EIGENSTRAIN HOMOGENIZATION METHOD FOR MULTISCALE POLYCRYSTAL PLASTICITY SIMULATIONS

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ABSTRACT

Crystal plasticity finite element (CPFE) and spectral methods are widely used to simulate and characterize the viscoplastic response of metals and alloys at microstructural scales. These direct methods remain computationally expensive for the characterization of single scale problems with complex microstructural features, as well as for multiscale analyses. The need for higher computational efficiency in this regard motivates the development of reduced order modeling (ROM) strategies. However, most of the existing reduced order modeling strategies typically require a costly construction (or training) stage to build the reduced order basis, which rely on executing simulations using the costly direct methods that the ROM intends to replace. In context of the reduced order eigenstrain homogenization method (EHM), a series of linear elastic microscale equilibrium problems need to be solved for computation of localization and interaction tensors prior to the reduced order nonlinear simulation. These microscale equilibrium problems are typically solved using either the numerical methods (finite elements, generalized finite elements) or semi-analytical methods (self-consistent, Mori-Tanaka). In this study, an efficient model construction strategy for the eigenstrain homogenization method (EHM) is presented using a reduced order spectral method. Inherently, spectral methods allow for direct solution of compatible strain fields without the need for resolving displacement field. Further, developed method leads to a small stiffness matrix that scales with number of partitions rather than number of degrees of freedom in the finite element mesh. Reduced order spectral method maintains high accuracy in computed response fields for low contrast materials. We show that a speedup of higher than an order of magnitude can be achieved compared to a finite element code for single-phase polycrystals. We further discuss the accuracy and scalability of the method for larger polycrystals and increasing phase contrast.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A METHODOLOGY FOR PRIORITIZING SIMULATION-BASED STRESS TESTS FOR TRANSPORTATION SYSTEMS

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ABSTRACT

Transportation systems are integral to the economic development and prosperity of communities. Their service, however, is affected by disruptive events causing economic and socio-economic consequences. To ensure these consequences are acceptably minimal under various disruptive scenarios, stress testing, as a diagnostic approach, has shown promise. A stress test, in this context, represents a stressed situation, where at least one variable describing the system, e.g., hazard intensity or performance of assets, is significantly worse than expected.

Nasrazadani et al. (2024) proposed a method to define and conduct simulation-based stress tests on transportation systems. Their approach entails an initial reference risk assessment, where the system is in its baseline condition, followed by conducting stress tests, which represent stressed situations. Although simulation-based stress tests offer detailed insights into system's resilience, their computational demand makes it impractical to conduct all potential tests in real applications. The challenge remains in determining which stress tests, among numerous possibilities, are more critical to be conducted. To address this gap, this research proposes a novel computationally efficient method to prioritize candidate stress tests.

The proposed methodology features a novel implementation of importance sampling approach that utilizes only the results of the reference assessment to identify which stress tests, if were to be conducted explicitly using simulations, would potentially have a higher impact on elevating the risks. For each stress test, a resampled subset of the results of the reference assessment is selected such that it would realize the specific conditions of that stress test, and thus its potential impact on risks. Those stress tests that are shown to lead to higher increase in risks in this approach are expected to do so as well if conducted explicitly, and hence deemed more critical. The methodology is applied to a road network in Switzerland subjected to extreme scenarios of rainfall flooding and landslides.

The proposed methodology allows infrastructure managers to conduct a screening analysis of candidate stress tests, identify the critical ones without explicitly conducting them, and allocate resources to conduct only the most critical ones. This reduces the number of potential scenarios while maximizing insights into the system's resilience. Additionally, it identifies which stress tests, if improved by taking risk-reducing measures, can contribute to higher improvement in system's resilience.

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Nasrazadani, H., B. T. Adey, and L. Dorren. 2024. "Simulation-based Stress Tests: Integrated Simulation Approach for Assessing Resilience of Transport Systems under Multiple Stressors." J. Infrastruct. Syst., (in press).

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A COARSE-GRAINED “THEOREMA EGREGIUM” FOR ORIGAMI TESSELLATIONS

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ABSTRACT

In his remarkable theorem, Gauss derives an expression for Gaussian curvature in terms of the metric tensor and its derivatives. Accordingly, there can be no change in the Gaussian curvature without a change in the metric. It is well-known that the same does not hold “on average”. For instance, the folding of origami tessellations is metric-preserving and yet produces large effective Gaussian curvatures. Our purpose is to derive a “coarse grained Theorema Egregium”, i.e., the rules that replace Gauss’ theorem “on average”. The main result is an equation that relates changes in the effective metric to changes in the effective normal curvatures. Such an equation has been stated as an equality of in-plane and out-of-plane Poisson’s coefficients in earlier work. Here, we present a unifying perspective anchored in surface geometry and asymptotic analysis. The proposed theory applies to any periodic piecewise smooth origami tessellation, be it developable or not. It excludes tessellations with holes or cuts but includes tessellations that are smoothly bent, with straight creases and/or curved creases. Various conclusions on the flexibility and rigidity of origami tessellations are explored. Finite element simulations carried over thin elastic shells support the findings.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETECTING CRITICALITY IN FIBRE REINFORCED CEMENTITIOUS COMPOSITES USING NATURAL TIME ANALYSIS OF ACOUSTIC EMISSION UNDER FLEXURAL LOADING

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ABSTRACT

This article presents the detection of criticality in ultra high performance concrete (UHPC) using natural time analysis of acoustic emission (AE). The unnotched UHPC beams with and without coarse aggregate, namely UHPC(CA) and UHPC(NCA), respectively, were prepared and subjected to flexural three-point loading. The beams were tested under displacement control with a loading rate of 0.2 mm/min. Simultaneously, the generated AE waveform parameters were recorded using an eight channel AE monitoring system. In the present study, the AE method is used in conjunction with the natural time analysis, which has been widely used to study the dynamic evolution of complex physical systems, which in our case is the specimen under mechanical loading. It provides valuable insights into the process of crack evolution within a system approaching the critical stage. The parameters, namely, variance (κ), entropy (S), and entropy under time reversal (S_), were studied in natural time (χ). Furthermore, an effort was made to correlate the criticality identified through the parameters by utilizing the cumulative AE energy. It was observed that the criticality occurs when the parameter κ reaches the value of 0.070 before failure, resembling the pattern observed before significant earthquakes. In addition, the observed complex behaviour can be comprehended through either the Olami-Feder-Christensen (OFC) earthquake model or the Burridge-Knopoff (BK) train model. Therefore, the parameter κ could be utilized as a predictive failure indicator, identifying the system's entrance into the critical stage of impending macroscopic fracture. The present findings may find its practical significance in determining the failure time of cementitious composites under increasing mechanical loads.

Keywords: self-organized criticality, ultra high performance concrete (UHPC), natural time, acoustic emission, fracture, predictive failure indicator.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NON-EXTENSIVE STATISTICAL MECHANICS OF FRACTURE IN FIBRE REINFORCED CEMENTITIOUS COMPOSITES USING ACOUSTIC EMISSION

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ABSTRACT

This article presents the investigation of non-extensive statistical mechanics (NESM) of fracture in ultra high performance concrete (UHPC) using acoustic emission (AE). The unnotched UHPC beams, with and without coarse aggregate, were prepared and subjected to flexural loading under constant displacement control. The NESM can capture unique features useful for understanding the complex dynamics of fracture, including long-range interactions, multifractal geometries, and long-term memory effects, which are distinctive features of the fracture process in concrete. The notion of NESM was applied to the inter-event time (τ), inter-event distance (D) between two consecutive AE events, and the AE scalar moment distributions (M) obtained from the recorded AE waveform parameters. Furthermore, the inter-event time distribution results were studied using superstatistics, which incorporates multiple local statistical distributions and complements the NESM concept. The complementary cumulative distribution function (CCDF) of τ, D, and M was reasonably modelled by the q-exponential function, and their corresponding q-index, namely, qτ, qD, and qM, respectively, were obtained. It was observed that the entropic indices, qτ and qM, were greater than one and hence were characterized by the super-additive process, while qM represented a sub-additive process with a value less than one. The sum of the entropic index for temporal and spatial distributions, qτ and qD, was two, supporting the concept of non-extensive spatio-temporal duality, which conforms with the previous research studies. In addition, the findings derived from superstatistics indicated that the nucleation and propagation of the cracks responsible for generating AE are characterized by a low degree of freedom.

Keywords: non-extensive statistical mechanics, fracture, ultra high performance concrete, acoustic emission, superstatistics, spatio-temporal duality.

AN EXTENSION OF THE WIENER PATH INTEGRAL TECHNIQUE TO ACCOUNT FOR POISSON WHITE NOISE PROCESSES

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ABSTRACT

The Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear dynamical systems relates to treating the system response joint transition probability density function (PDF) as a functional integral over the space of all possible paths connecting the initial and the final states of the response vector [1]. Further, the functional integral is evaluated, ordinarily, by resorting to an approximate approach that considers the contribution only of the most probable path. This corresponds to an extremum of the functional integrand and is determined by solving a functional minimization problem that takes the form of a deterministic boundary value problem. However, the validity of the WPI formalism is restricted, to-date, to excitations modeled as Gaussian white noise processes. Note that a wide range of non-Gaussian and/or non-white processes can be accounted for, within the same framework, by augmenting the state-variable vector and by utilizing additional auxiliary filter equations [2]. Herein, the WPI technique is extended to treat, in a direct manner, cases of stochastic excitations modeled as Poisson white noise processes. This is done by employing an appropriate expression for the short-time transition PDF [3], and by deriving a novel representation of the system response PDF as a functional integral over the space of possible paths. The reliability of the technique is demonstrated by comparisons with pertinent Monte Carlo simulation data.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE EXISTENCE, UNIQUENESS AND EFFICIENT CALCULATION OF WIENER PATH INTEGRAL MOST PROBABLE PATHS FOR A CLASS OF NONLINEAR STOCHASTIC DIFFERENTIAL EQUATIONS

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ABSTRACT

The Wiener path integral (WPI) technique for determining the stochastic response of diverse nonlinear dynamical systems treats the system response joint transition probability density function (PDF) as a functional integral over the space of all possible paths satisfying the initial and final states of the response vector [1]. This functional integral is evaluated, ordinarily, by resorting to an approximate approach that considers the contribution only of the path with the maximum probability of occurrence. This is referred to in the literature as the most probable path and corresponds to an extremum of the functional integrand. Further, resorting to calculus of variations yields the Euler-Lagrange equation that takes the form of a deterministic boundary value problem (BVP) to be solved for the most probable path [2].

Herein, it is shown that for a class of stochastic differential equations with nonlinear drift and diffusion coefficients, there exists a unique solution, over a specific region, to the most probable path BVP. Further, a computationally efficient iterative solution approach is developed for the most probable path. Various numerical examples pertaining to oscillators exhibiting diverse nonlinearities are included for demonstrating the reliability of the developed approach. Comparisons with pertinent Monte Carlo simulation data are included as well.

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NUMERICAL INVESTIGATION OF WAVE SCOUR AROUND TANDEM CYLINDERS

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ABSTRACT

Understanding the wave-driven scouring around cylindrical structures is important for the design and safety of hydraulic structures. The scour and flow around vertical cylinders exposed to waves are investigated using three-dimensional numerical model SedFOAM, a two-phase Eulerian-Eulerian multiphase flow solver based on OpenFOAM® framework. The flow turbulence is modeled with large-eddy simulation (LES). The solid phase pressure and viscosity were modeled using kinetic theory of granular flows. The numerical simulation results were validated against the experimental observations reported in Sumer, B. M; & Fredsøe, J. (1998) Wave scour around group of vertical piles. Journal of Waterway, Port, Coastal, and Ocean Engineering. Results of series of numerical simulations with varying gap to diameter ratio were analyzed. The development of scour hole and near-bed vortex field was thoroughly examined. Bed shear stresses from numerical simulations are compared to the experimental values. In addition to the validations mentioned, we will discuss the role of coherent eddy structures on the development of the scour hole.

A NOVEL APPROACH TO OVERHANG CONSTRAINTS IN TOPOLOGY OPTIMIZATION

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ABSTRACT

Free-form topology optimization (TO) yields parts with superior performance, as has been documented in the literature. With ongoing advancements in additive manufacturing (AM) techniques, the realization of these high-performance parts in real-world applications is now more attainable than ever. However, traditional AM processes involve the addition of support material for unsupported regions, leading to time-consuming, expensive, and sometimes impractical removal processes. To address this challenge, it is beneficial and sometimes necessary to design parts that eliminate the need for support materials during printing, often referred to as an overhang constraint in design.

The issue of overhang constraints has been an active area of research in TO, and current state-of-the-art approaches typically employ a projection- or filter-based overhang constraint to ensure sufficient support for all regions within the design domain [Gaynor 2016, Langelaar 2017]. While effective, this method (particularly the sensitivity analysis) can be complex to implement efficiently and can struggle in design problems where overhang constraints severely reduce part performance. In response, we propose a novel, more simple method for implementing overhang constraints in TO. We discuss practical implementation of this approach and explore the implications of different regularization methods for the overhang constraint on design and support features. To validate the efficiency and scalability of our proposed method, we present several numerical examples across a diverse set of applications.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARATIVE ANALYSIS OF HURRICANE REGIONAL ANALYSIS PLATFORMS: IN-CORE, PRAISYS, AND NHERI’S SIMCENTER

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ABSTRACT

With the growing number of regional analysis platforms and the diverse goals of community resilience research, there is a demand for an understanding of each platforms' strengths. More so, there is a demand for users to know which platforms are geared toward their skills, goals, and available data in the regional analysis field. For instance, city planners pursuing community resilience models may lack the coding language or the platform-specific software background required to run regional resilience analysis or Catastrophe Modeling applications efficiently and accurately in a particular program. Having resources that detail the skills required for different platforms will allow for more specific training or the development of front-end software.

A comparative study of hurricane regional analysis platforms was conducted to bring light to platforms' accessibility to a user audience broader than developers and regional analysis researchers. Various platforms (including IN-CORE, NHERI's SimCenter, and PRAISys) were qualitatively assessed using three categories: Ease of Data Synthesis, Time Saving, and Tool Usage Communication,

Test studies aimed to analyze the loss of functionality on a regional scale while qualitatively assessing the three platforms' usability from a third-party perspective. The same test study was conducted using each platform with historical wind speed data on Hurricane Ian. The analysis of damages to power line transmission networks in Florida was used with previously developed fragility curves. A functionality analysis allowed work on each platform's process and supporting software.

The topic of the test study was chosen to support ongoing research on electric power networks in Florida subjected to hurricane hazards. Additionally, hurricane analysis on power networks is supported by each platform.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING MICROCAPSULE TRANSPORT IN FRACTURED MEDIA THROUGH COUPLED CFD-DEM METHODS

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ABSTRACT

Geothermal energy seems like a promising solution to our energy crises and environmental issues. However, challenges such as production temperature, flow rate, and thermal breakthrough time have been affecting its efficiency. In this presentation, we propose an innovative solution by injecting polymer-based microcapsules into fractures to modify permeability and prevent preferential flow, which can lead to a thermal breakthrough. Using coupled computational fluid dynamics and discrete element method (CFD-DEM), we explored scenarios involving microcapsule size, concentration, and fracture roughness. Our results indicate that in smooth fractures, small microcapsules easily travel, while larger ones do so at lower concentrations, and mixed-size ones tend to seal the fracture. In rough fractures, microcapsule transport complexity increases due to interactions with rough walls. The results suggest that complex fracture surfaces increase sealing behavior, which could be mitigated using smaller and lower concentrations of microcapsules.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF OSMOTIC PRESSURE GRADIENTS ON WATER DIFFUSION AND HYDRAULIC FRACTURING OF MAFIC ROCKS AIMED AT SUSTAINABLE DEEP SEQUESTRATION OF CO2

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ABSTRACT

The ultimate goal is a sustainable CO2 sequestration system operating for decades. This is to be achieved by injecting under sufficient pressure water with dissolved CO2 into a deep formation of mafic rock, specifically peridotite. The technology would be the inverse of the fracturing of gas or oil shale, but with some important differences. The peridotite contains a system of random cracks which are only partly connected while the shale contains a system of parallel closed or cemented cracks which are prone open under under hydraulic pressure. Important is water diffusion through the pores, which creates stresses needed to open sideways cracks. The gradients of osmotic pressure due to differences in ion concentrations in rock and injected water offer a possibility to manipulate the diffusion and lateral crack opening. The differential equations and boundary conditions governing the problem are formulated and solved numerically. The purpose is twofold: 1) to develop a rock permeability test that includes the effect of osmotic pressure gradient and distribution, which does not exist at present. This test, which is being developed at University of Minnesota in collaboration with Northwestern, will utilize measurement and analysis of pressure decay in an almost rigid chamber after injections of water of different salinities. 2) The second purpose is to prepare a computational model for a subsequent study on hydraulic fracturing in presence of osmotic pressure gradients in rock.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRESS-BASED PHASE-FIELD FRACTURE MODEL FOR ICE AND ROCK FRACTURE SIMULATION

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ABSTRACT

Forecasting the behavior of complex fractures in ice and rock materials is crucial for understanding the failure risk from hanging glaciers in high mountain Asia. This issue is becoming a pressing concern with a warming climate impacting mountain glaciers worldwide. While hydrodynamic models are typically used to model ice-rock avalanches, fracture is a precursor and often occurs in the quasi-static regime. Computational models with superior accuracy and reliability for predicting ice-rock fracture are needed to understand the failure initiation mechanisms in hanging glaciers. Phase field fracture models have the potential to address this need, but they need to undergo rigorous verification, calibration and validation. To this end, we employed a stress-based phase-field fracture model (Clayton et al., 2022) to simulate fracture propagation within ice-rock medium. To ensure our model reflects reality, we first verify the model's ability to simulate complex 2D and 3D fractures by utilizing the experimental studies presented in the damage mechanics challenge (DMC) (Jiang et al. 2022).

In our presentation, we will discuss the governing equations of the stress-based phase field model tailored to simulate predominantly tensile fracture in brittle ice/rock materials. We will detail its verification, calibration and validation using linear elastic fracture mechanics and experimental data from the DMC. Additionally, we will explain how we have applied our model to the specific context of Himalayan glaciers and outline our strategies for managing large-scale glacier simulations using the h-adaptive finite element method (Gupta et al. 2022). Our results show that our model is able to accurately predict fracture and load-displacement curves, with 5% to 10% error margin compared to experimental data. Our preliminary simulations of idealized ice-rock cliffs reveal that rock fracture may be more crucial for hanging glacier failures.

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Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCED AI-DRIVEN CORROSION DETECTION USING IMAGE SEGMENTATION, DEEP NEURAL NETWORKS, AND ENSEMBLE LEARNING

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ABSTRACT

Corrosion mitigation represents a significant expense in the United States, accounting for 40% of the maintenance budget and exceeding $20 billion annually across both military and civil infrastructure. This presents a substantial economic challenge, particularly for the U.S. Army Corps of Engineers (USACE). This study introduces a novel AI-driven method for detecting and segmenting corrosion, employing an ensemble of three advanced deep learning models. It aims to autonomously identify and segment corroded areas in high-resolution images. This process encompasses data annotation, preprocessing, augmentation, model implementation, and performance evaluation. The employed deep learning models include a Feature Pyramid Network (FPN) with a ResNet-34 encoder, UNet with a ResNet-34 encoder, and UNet++ with a VGG-19 encoder. By combining these models through ensemble learning, we significantly improve prediction accuracy and overall performance. The effectiveness of this method is evidenced by its notably high Dice score (also known as F1 score) and Intersection over Union (IoU) score. This method shows significant potential for automating corrosion detection and quantification, potentially lowering inspection costs and aiding in early identification of critical issues to prevent structural failures. Further development focus on adapting this tool for real-world applications in large-scale infrastructure corrosion prediction and identification.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISION-BASED STRUCTURAL DISPLACEMENT MEASUREMENT USING TRANSFORMING MODEL PREDICTION

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ABSTRACT

Due to the deterioration of civil infrastructures, monitoring the condition of the structural are becoming more important. One of the most popular methods to assess the condition of the structure is to measure the dynamic displacement of the structure. However, conventional methods require installing an instrument such as erecting a scaffold on tested structure which may affect the response of the structures. Vision-based measurement has been rapidly known as a non-contact type due to the development of high-speed industrial cameras and image processing technology. Although these studies have demonstrated the effectiveness in structural displacement measurement, several limitations have been pointed out. First, most studies relied on the region of interest at the first video frame, which is sensitive to the environmental conditions. Second, the target object was mainly a checkerboard which is easy to extract feature points. In real world situations, the experiments are prone to fail if the feature points get lost due to the change in background noise and occlusion. To overcome these aforementioned limitations, this study proposed a deep learning-based method using Transformer tracking, which adapts the self-attention mechanism to capture both local and global information on the video frame. To validate the performance of this method, the analysis was conducted in a simulation-based experiment, a lab-scale experiment, and on-site experiment. The proposed method enhances the overall tracking robustness against occlusion and brightness condition.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING BRIDGE PERFORMANCE AND ITS EFFECTS ON TRANSPORTATION NETWORK RESILIENCE UNDER HURRICANE STORMS

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ABSTRACT

The resilience of a transportation network is significantly influenced by the performance of bridges when subjected to extreme weather events such as hurricanes. This research builds a comprehensive framework for resilience estimation, particularly in the context of hurricanes. Two areas along the southern coast of Texas were chosen as testbeds. Utilizing the hazard data of 446 synthetic storms, the research determined the distribution of storm intensity measures for each bridge within the transportation network. Performance-based assessments were conducted to estimate the probability of bridge damage states using Monte Carlo Simulation and fragility analysis. Then, a transportation network simulation model was performed to assess the impact of bridges on the overall transportation network. Performance indices, such as travel time, speed, economic losses, and the loss of accessibility, were employed to develop the resilience index. Diverging from previous studies, this research proposes a multi-faceted resilience index that encapsulates robustness, rapidity, redundancy, and resourcefulness, each serving as a discrete sub-index within the overarching resilience framework. Mitigation strategies were optimized and analyzed in the two testbeds, and the resultant resilience indices were compared. The findings indicated the efficiency, accuracy, and comprehensiveness of the assessment framework. This approach provides an effective tool for decision-makers and engineers to evaluate the vulnerability of transportation networks and to devise more robust mitigation strategies to counter the threat of hurricanes.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL-TIME HYBRID SIMULATION FOR FLOATING WIND TURBINES: CHALLENGES AND SOLUTIONS IN FORCE CONTROL FOR FLUID-STRUCTURE INTERACTION TESTING

Yun Ni[1], Akiri Seki[1], Bret Bosma[2], Barbara Simpson[1], Ted Brekken[2], Bryson Robertson[2], Bryony DuPont[2], Andreas Schellenberg[3] and Pedro Lomonaco[2]*

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[2]Oregon State University
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ABSTRACT

The response of floating offshore wind turbines is subject to multiple physical interactions, including coupling effects between aerodynamic, hydrodynamic, and structural dynamic forces. However, satisfying dynamic equilibrium for small-scale experiments employing multiple governing forces is difficult due to incompatible similitude laws. This study explores the application of Real-Time Hybrid Simulation (RTHS) as a solution to address scaling conflicts between different forces encountered in small-scale testing. The control accuracy of a force control methodology is explored for a 1:50 scaled floating specimen in a wave basin. The hydrodynamics, platform, and tower are experimental while the applied aerodynamics is numerical and applied via robotic arm actuation. Challenges and lessons learned in implementing the force control design are outlined, such as the treatment of noise, disturbance rejection and application of robot arm kinematics. Additionally, a modified Adaptive Time Series (ATS) compensator for force control is proposed to address latency issues within the RTHS system. By highlighting the potential of RTHS and alternative force control strategies, valuable insights can be gained on how best to mitigate the unique challenges associated with force control on floating specimens in fluid-structure interaction testing.

A FRAMEWORK FOR DAMAGE DIAGNOSIS FOR MITER GATES OF NAVIGATION LOCKS

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ABSTRACT

Structural integrity of navigation locks' miter gates is critical for operational safety and sustainability of navigation thorough waterways. Conventional methods for identifying damage in these structures encounter difficulties due to insufficient data and complex damage patterns. They often focus only on one aspect of damage diagnosis: detection, localization, or severity quantification. We develop a comprehensive framework that uses limited strain gauge data, advanced signal processing, and machine learning (ML) algorithms for damage detection, localization, as well as severity quantification in miter gates.

The proposed methodology employs finite element models of miter gates to generate synthetic strain data corresponding to different damage scenarios. This approach compensates for the unavailability of real-world strain data for different damage configurations (location and severity). We use wavelet transform and Fourier analysis to extract key features from the high-dimensional strain data. This helps extracts the most important features indicative of structural damage. We then train multiple ML models for damage diagnosis. An LSTM autoencoder-decoder model is employed for damage detection. This model identifies anomalies in time-series strain data. For damage localization, we develop a graph neural networks (GNN) model. The GNN learns the (spatial) relationships between the strains measured by different strain gauges to identify damage location. The severity of the damage is quantified using Gaussian Process Regression (GPR) models, which learn the relationship between strain data characteristics with damage severity. We also develop adaptive learning and feedback loop for re-training these diagnostic models. The diagnostic models are continually refined using new data. We demonstrate the proposed methodology by diagnosing damage in the downstream miter gate of the Racine main lock on the Ohio River.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCEMENT LEARNING FOR ADAPTIVE BATTERY MANAGEMENT OF STRUCTURAL HEALTH MONITORING IOT SENSOR NETWORK

Tahsin Afroz Hoque Nishat[1], Jong-Hyun Jeong[1], Hongki Jo[1] and Jian Liu[1]*

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ABSTRACT

Battery-powered wireless sensor networks (WSN) offer a cost-effective and easy-to-deploy solution for Structural Health Monitoring (SHM) applications. Despite their potential, the long-term operation of WSN becomes challenging due to uneven battery degradation across various sensor nodes, battery replacement logistics, and the assurance of SHM Quality of Service (QoS). Prolonging battery life through a system-level battery health management strategy is crucial for extended, reliable, and cost-effective WSN operation, especially considering the expensive maintenance trips required for battery replacement. This study develops a reinforcement learning (RL) based framework for active control of battery degradation at the WSN system level without sacrificing the SHM QoS. The primary objective is to strategically replace batteries as groups, thereby minimizing associated logistics and extending the service life of WSN while ensuring the desired QoS at the system level. To validate the developed RL framework, a comprehensive simulation environment was established within a real-life WSN setup for a cable-stayed bridge SHM. The simulation considered a spectrum of WSN operational factors e.g., solar harvesting variations due to weather conditions, communication uncertainties, lithium-ion battery degradation model, power consumption of accelerometer sensors, and duty cycles strategy, etc. We also introduce a mode shape-based quality index threshold for demonstration purposes. The RL agent underwent training in the developed environment to learn optimal node selection for a particular duty cycle. The training and test results underscore the effectiveness of the proposed framework in addressing battery-related challenges and ensuring the sustained operation of WSNs in practical applications.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CFD-BASED COMMUNITY-LEVEL HURRICANE WIND HAZARD MODELING USING INTEGRATED BIM-GIS APPROACH

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ABSTRACT

Hurricane-induced wind hazard causes significant damage to coastal communities with severe consequences on the built environment and the social systems. The ability to quantify accurate wind loads on buildings will enable better damage assessment and better planning for recovery. Most of the current wind models are building-level based and don’t account for the surrounding topography and built environment. While recently there have been multiple studies on the impact of the urban topology on the wind flow, it still lacks appropriate modeling of the wind flow at the community-level. The current community-level wind hazard modeling did not comprehensively investigate the application of computational fluid dynamics at the community-level. In this research, a novel approach was developed to conduct wind hazard modeling at the community-level using computational fluid dynamics along with BIM-GIS integration approach to discretize the geometry of the community. A high-resolution community model was developed by modeling the geometry of the different building typologies within the community. A GIS shapefile of the community with detailed building information (e.g., building footprint, number of stories, foundation type, first-floor elevation, and roof shape) was used as input for a parametric BIM model to generate the geometry of each building within the community. The final generated geometry of the community is used as an input for a numerical wind tunnel that uses an Open-FOAM solver to conduct CFD analysis to account for detailed wind flow and wind pressure at the building level after including wind aerodynamics at the community-level. The developed approach allowed to capture many phenomena such as the sheltering effect that cannot be captured using building-level analysis. This proposed approach provides the basis for the next generation of high-resolution community-level CFD wind hazard modeling.

INTERDEPENDENT POST-HAZARD FUNCTIONALITY ASSESSMENT APPROACH FOR BUILDINGS EXPOSED TO FLOOD HAZARDS

Omar Nofal[1], Nathanael Rosenheim[2], Sabarethinam Kameshwar[3], Jayant Patil[4], Xiangnan Zhou[4], John van de Lindt[5], Leonardo Duenas-Osorio[4], Eun Jeong[6], Amin Endrami[7], Elaina Sutley[7] and Chen Wang[6]*

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ABSTRACT

Flood hazards are one of the most frequent natural hazards around the world and result in many social and economic consequences. Quantifying the post-hazard functionality is essential to track the performance and recovery of communities following flood hazards. There are many studies on vulnerability and post-hazard functionality for buildings with a main focus on the physical part of the functionality and less focus on the socio-economic perspective of it. Although physical damage is essential to quantify the functionality of buildings following a severe flooding event, it is not sufficient for a comprehensive post-hazard functionality assessment. Therefore, in this research, a community-level multi-scale approach was developed to quantify the post-hazard functionality for buildings exposed to flood hazards. The developed methodology takes into account the physical functionality of the building, the availability of power and water, and the accessibility to essential services such as gas stations, shopping centers, schools, and hospitals. The novel contribution of this research is the ability to develop socio-physical formulation that accounts for the interdependencies between the functionality of physical systems and socio-economic systems which is the key to measure resilience at the community-level. The analysis resolution of the developed approach is at the household and housing unit-level which allows to capture very detailed population dynamics to account for socio-economic activity and its impacts on the total post-hazard functionality of buildings. The developed approach is general and can be applied to any community and for any hazard with the appropriate modifications to accommodate the different hazard characteristics.

Structural reliability, bridges, and truck loads
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATISTICAL ANALYSIS OF EXTREME LIVE LOAD EFFECTS ON INDONESIAN BRIDGES

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ABSTRACT

This study investigates the live load effects on simply supported beam bridges by considering important factors such as vehicle weight, speed, axle spacing, and following distance. The analysis utilizes data from the Pawiro Baru Bridge weigh-in-motion (B-WIM) system, located in the Northcoast of Central Java National Road, Indonesia. The site of the B-WIM system is characterized by high numbers of heavy vehicles and high traffic volume. Data collected over one year is employed to analyze the live load characteristics and assess their impact on bridge structures. Finite element models are developed for four types of simply supported beam bridges with spans ranging from 25 to 40 meters, and moving load analysis is conducted to simulate traffic loading conditions. By employing statistical methods of extremes, the maximum value distribution of live load for a bridge's projected 75-year lifetime is determined. The results indicate that the mean value of the live load for the simply supported beam bridges, based on B-WIM measurements of actual traffic flow, is lower than the nominal design live load specified by the SNI 1725 2016 Bridge Loading code. However, the standard deviations and distribution data obtained from the study offer valuable insights for the reliability-based evaluation of standard-designed simply supported beam bridges in Indonesia. This research contributes to enhancing the understanding of live load effects on Indonesian bridges, particularly in the context of simply supported beam bridges. By incorporating B-WIM measurements and statistics of extremes, accurate assessments of live load characteristics are made possible.

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Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CORNER SUPPORTED THIN LAMINATED COMPOSITE PLATES

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ABSTRACT

In the past few decades, plates made of laminated composite materials have attracted the attention of many engineers and designers due to their favorable properties of high strength to weight ratio and stiffness. The behavior of thin laminated plates having a general stacking sequence is governed by three coupled partial differential equations, derived based on the “Kirchhoff plate theory”. Analytical solutions of these equations have been obtained for cases involving simple geometries and boundary conditions. One of the important and practical boundary conditions which is not fully addressed yet is the corner supported plate. The purpose of this study is to propose a Ritz method-based approach for obtaining an accurate solution for a uniformly loaded corner-supported thin laminated composite rectangular plate having a general stacking sequence. In the proposed approach, Ritz method is cast in a matrix form and an automated symbolic integration procedure is used to allow the use of many approximating polynomial terms as required for convergence. The accuracy of the proposed method is validated by comparing the results obtained against those finite element method (FEM) solutions generated using the commercial software ABAQUS.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PROBABILISTIC MODEL FOR SPATIALLY VARYING TENSILE STRENGTH: STRENGTH RATIOS

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ABSTRACT

The natural growth of wood leads to significant variation in the mechanical properties of dimension lumber, which is used as constituent lumber in CLT fabrication. Strength varies due to the presence of features, such as knots, but also due to natural variation in clear wood. A previous research initiative presented at the 2023 Engineering Mechanics Conference resulted in a probabilistic model for spatially varying tensile strength in dimension lumber that decoupled spatial variation in clear wood tensile strength and the influence of the distribution and geometry of knots. The tensile strength spatial variation in dimension lumber was simulated by applying the Monte Carlo method and superimposing the spatial variation in clear wood with a strength ratio dependent on the probabilistic geometry of knots.

The strength ratio utilized in previous work considered only the knot area ratio and the associated reduction in cross-sectional area to transfer the load. However, knots develop complex stress concentrations and eccentricities when located on the edge of boards. As such, the strength ratio previously employed neglected important factors driving strength reduction associated with knots. This work develops two alternative strength ratios for improved accuracy of the model. These strength ratios are developed by leveraging empirical expressions for stress concentration factors of holes and notches in finite width planes. Finite element models are developed and compared to the empirical expressions. Finally, the new strength ratios are employed in the previously developed model for spatial variation in tensile strength.

The overarching goal of this work is to provide a framework for a higher fidelity treatment of board-scale tensile strength properties in lumber to provide more reliable uncertainty characterization of strength. This framework could be incorporated into a probability-based design process that utilizes a more sophisticated description of strength variation and associated uncertainty. The current design process utilizes a uniform allowable design strength within a given species and grade. For strength properties, the allowable design value is based on the characteristic value, which corresponds to the fifth percentile of a probability distribution model resulting from experimental testing. A higher fidelity treatment of board strength variation would allow for a more precise and accurate description of wood properties, which could carve a pathway for greater utilization of traditionally low-value wood species in structural applications and higher material efficiency in mass timber construction.

Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ROCK AGGREGATE PULL-OUT TEST IN CONCRETE: EVALUATION OF BOND STRENGTH AND INTERFACE BEHAVIOR BETWEEN ROCK AGGREGATES AND CONCRETE

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ABSTRACT

In recent years, there has been a growing interest in using supplementary cementitious materials (SCMs), such as slag and fly ash, in concrete mixes due to their potential to improve concrete properties, including bond strength. SCMs can enhance the durability and performance of concrete in several ways, including by reducing the permeability of the concrete matrix and increasing the resistance of the concrete to chemical attack. However, using SCMs in concrete mixes can also impact the bond strength between rock aggregate and concrete mix interface. Properly evaluating bond strength and interface behaviour between rock aggregates and the surrounding concrete mix is crucial for designing durable and high-performance concrete structures. In this work, we experimentally investigated the use of Ordinary Portland Cement (OPC), slag, and fly ash in combination with both normal coarse rock (NA), recycled rock aggregates (RA), and fiber in the bond strength and interface behaviour between rock aggregates and the cement matrix in concrete through rock pull-out test at different curing ages. The findings highlight the influence of OPC and supplementary cementitious materials on the interfacial transition zone (ITZ) properties, which play a critical role in the bond strength between rock aggregates and the surrounding concrete matrix. Compared to plain concrete, fiber-reinforced concrete (FRC) specimens exhibit higher bond strength and enhanced crack resistance at the interface. The specific fiber type significantly affects the interface behaviour, leading effectiveness of fibers in bridging cracks and delaying their propagation, contributing to the observed improvements in bond strength and interface toughness. This study demonstrates the efficacy of the rock aggregate pull-out test for evaluating bond strength and interface behaviour in plain concrete and FRC. The findings provide valuable insights into the influence of fibre characteristics on these crucial parameters, paving the way for the optimization of FRC mix designs and enhanced concrete performance.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LONG-RANGE ISING MODEL FOR PERFORMANCE STATES IN REGIONAL SEISMIC ANALYSIS

Sebin Oh[1], Sang-ri Yi[1] and Ziqi Wang[1]*

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ABSTRACT

The application of Performance-Based Earthquake Engineering (PBEE) to regional-scale analysis entails the computation of performance states of a large set of structures [1]. Physics-based simulations or probability distribution-based simulations can be employed for this computation. The former could realistically capture the regional response, including the correlation in performance states of different structures as well as the correlation between ground motion intensity measures. However, demanding computational costs for large-scale analysis often restrict the use of physics-based simulations to scenario-specific analysis. The latter, representatively the fragility curve-based approach, is computationally efficient and offers statistical descriptions, but it can oversimplify the regional behavior depending on the underlying assumption. For example, directly assembling fragility curves for each structure under independence assumption can lead to a large underestimation of the global failure probability of a region [2]. Besides, the lognormality assumption of fragility curves was originally motivated by its mathematical convenience rather than clear statistical or physical rationale [3].

In this study, we propose the Ising model from statistical physics as a joint probability distribution for binary states (safe/collapse) of structures for regional seismic analysis. The Ising model leverages the principle of maximum entropy to convert the pre-specified statistical information up to the second-order moment into a joint probability distribution, avoiding the use of artificial assumptions. Since the Ising model only requires second-order statistical information, the proposed method does not require additional efforts beyond current PBEE practices. To demonstrate the effectiveness of the proposed approach, the Ising model for a neighborhood in Pacific Heights, San Francisco, is constructed from fragility functions using the Regional Resilience Determination (R2D) tool provided by the SimCenter. Additionally, the Ising model driven from the post-earthquake survey data for a region in Antakya, Turkey, is presented, demonstrating the wide applicability. Based on the constructed Ising model for the two target regions, novel interpretations are also provided in the language of regional seismic analysis, further emphasizing the potential of the Ising model as an interpretable stochastic model that can be integrated into current practices.

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Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN NEURAL NETWORKS WITH PHYSICS-DRIVEN FUNCTIONAL PRIORS TO ENHANCE PREDICTIVE MODELING IN ENGINEERING MECHANICS

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ABSTRACT

Data-driven approaches and machine learning (ML) have become essential tools to enhance and accelerate predictive modeling in engineering mechanics. Neural networks (NNs) in particular show great performance in large-data settings. Engineering applications however are often characterized by relatively small amounts of data due to the high cost of data collection, whether it be from expensive simulations in surrogate modeling or costly experiments. In this setting it is imperative to 1) quantify epistemic uncertainties that arise from low data availability, which can help guide future data collection, and 2) integrate physics intuitions or knowledge from low-fidelity models to improve generalization performance away from training data. We argue that framing training of NNs within a probabilistic Bayesian framework allows to both quantify uncertainties and integrate physics intuitions through the prior. However, the high-dimensionality and non-physicality of parameters that characterize neural networks hinders both the design of a meaningful prior and posterior via existing Bayesian methods. In this talk I will present a new methodology to train Bayesian neural networks that leverages functional priors, where physics intuitions are easier to convey, ensembling for posterior inference. In addition, we leverage tempering during training to ensure an appropriate trade-off between reliance on the data, where it is available, and the prior, away from training data. We will illustrate the advantage of this new computational framework with both synthetic data on benchmark problems and applications to engineering mechanics.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIGHLY STRETCHABLE PANTOGRAPH-INSPIRED MULTI-LAYER LATTICE METAMATERIALS

Kehinde Omotayo[1], Mohammad Amin Hodaei[1], Paul Resch[1], Ranganathan Parthasarathy[1], Anil Misra[2], Landon Onyebueke[1], Catherine Armwood-Gordon[1] and Lin Li[1]*

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ABSTRACT

Lattice metamaterials which can magnify the elastic limit and fracture strain of their constituent parent materials are highly sought after in applications including wearable electronics and batteries, impact absorbents, switchable acoustic modulators, soft robotics, rehabilitation devices, tissue scaffolds, and drug delivery vehicles. Current strategies for increasing stretchability include kirigami and origami-based, serpentine, bi-layer, as well as pantographic designs. The former three of these designs rely on out-of-plane buckling to increase reversible deformation, while the latter two exploit torsional compliance between component layers. In this work, we present multi-layer pantograph-inspired lattice structures modeled on polygonal templates. Each strut in the unit cell belongs to an individual layer and is connected to the nearest neighbor struts in their respective layers via cylindrical connectors. The hexagonal and diamond unit cells were selected as polygonal templates since they are the only regular planar geometries that tessellate with themselves while reducing to linkage mechanisms when the joints between neighboring struts are hinges. The deformation of the lattice is accommodated by flexure-shear and torsion in the connectors, as well as stretching and bending of the struts. Proof-of-concept samples were additively manufactured using stereolithography from commercially available acrylate-based resins. Axial and flexural stiffnesses of the struts were made large enough that lattice deformation was predominantly accommodated in the cylindrical connectors by torsion at small deformations, and flexure-shear-torsion at large deformations. Experimental observations at the scale of individual elements were obtained using digital image correlation and effective elasticity tensors under plane stress were assembled. A discrete-to-continuum bridging was developed by homogenizing the lattice structures to effective continua using the granular micromechanics framework under the restriction of linear elasticity. In the discrete description, the joints between the struts were visualized as grains interacting with their nearest neighbors, with the elastic interaction energy being a function of the Euclidean distance between two grain pairs and the relative rotation between nearest neighbor inter-layer struts. The discrete-continuum kinematic relationships were developed as an interpolation between perfectly hinged cases and rigid joint cases. The experimental results show reasonable agreement with the granular micromechanics model for cases where the flexure-shear deformation of the cylindrical connectors is negligible. For slender connectors, the agreement was poor, and the effective values of intergranular stiffnesses are currently being re-examined. As expected from geometric compatibility analysis, the diamond lattice shows better strength retention under increasing stretchability as compared to the hexagonal lattice.

A new horizon - Quantum computing and quantum materials (by invitation only)
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELEMENT STIFFNESS-BASED MATRIX DECOMPOSITION FOR QUANTUM COMPUTING IMPLEMENTATION OF THE FINITE ELEMENT METHOD

Caglar Oskay[1], Abhishek Arora[1] and Benjamin M. Ward[1]*

[1]Vanderbilt University

ABSTRACT

Noisy Intermediate-Scale Quantum (NISQ) computers are reaching a state of development that is conducive to implementation of methods and algorithms relevant to engineering mechanics. In this study, a new implementation of the finite element method for hybrid classical-quantum computers (named Quantum Finite Element Method, or QFEM) is introduced. QFEM leverages the Variational Quantum Linear Solver (VQLS) approach, where the linear system resulting from the finite element construction procedure is posed as an optimization algorithm, in which function evaluations are performed on a quantum computer, whereas the search direction and step size are identified using a classical optimizer implemented in a classical computer. A primary limiting factor in the implementation of this methodology is efficient matrix decomposition that allows the stiffness matrix to be expressed as a linear combination of a series of unitary matrices. The focus of this study is leveraging the standard finite element assembly operation to efficiently construct a set of unitaries that does not necessarily scale with the size of the linear system (or with the number of qubits used). A generalized procedure for constructing quantum circuits that implement the unitary matrices resulting from the proposed algorithm is proposed. The implementation was verified using quantum simulators in the context of the solution of Poisson’s equation. Computational complexity and circuit structures associated with structured grids, unstructured grids, the presence of heterogeneous material constants, as well as using linear and quadratic finite elements are explored.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A STOCHASTIC HIERARCHICAL MULTISCALE MODELING FRAMEWORK FOR HETEROGENEOUS MATERIALS

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ABSTRACT

Multiscale modeling allows for the examination of materials that behave differently at different length scales. While this approach ensures a more accurate approximation of material behavior, it can be expensive to use because it requires the evaluation of a lower-scale model at every upper-scale integration point in time. Often, deterministic material properties are assumed on the lower scale, but this ignores the inherent stochasticity in many heterogeneous materials. We address these two problems in hierarchical multiscale modeling in two stages. First, we have developed finite element square approach to model heterogenous materials that considers stochasticity at the lower scale. We demonstrate this heterogeneity by modeling lower-scale material properties of interest as random fields. The Hierarchical Multiscale (HMS) Framework, a high-performance computing-based scale bridging framework developed at the Army Research Lab, is used to efficiently handle the computations including message passing across scales, parallel lower-scale model execution, and load balancing. The second part of this work aims to address the computational cost of the multiscale model by learning and deploying a stochastic surrogate model to replace the expensive lower-scale model. The surrogate model can be pre-trained offline and used during the execution of the multiscale model framework leading to significant computational gains in speed. In this ongoing work, we are further investigating the potential to actively learn the surrogate model online for further enhanced performance. The statistical properties of the response and the computational efficiency of the proposed framework will be demonstrated through dynamic analysis of a cantilever beam with stochastic heterogenous material.

ADVANCING MATERIAL GENOMICS WITH ACTIVE LEARNING AND BAYESIAN ANALYSIS IN POLYMER-BONDED EXPLOSIVES

Ozge Ozbayram[1], Maruthi Annamaraju[2], Andreas Robertson[2], Daniel Olsen[2], Min Zhou[2], Lori Graham-Brady[1] and Surya Kalidindi[2]*

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ABSTRACT

Addressing the complex challenge of understanding and predicting the material property of polymer-bonded explosives (PBX) under various conditions remains a critical yet unresolved issue in material genomics. We introduce a robust material informatics framework, employing a sophisticated batch active learning approach, to revolutionize the exploration of material structure-property relationships in high-dimensional design spaces. By integrating a Bayesian learning method, we not only address the multifaceted challenges of microstructure-property relationships but also significantly reduce reliance on costly physics-based simulations. This framework represents our vision for redefining the rapid design and discovery of advanced engineering materials, setting a new standard in material genomics research.

In our study, we focus on the shock-to-detonation transition (SDT) in polymer-bonded explosives (PBX), crucial for understanding their varied detonation responses to shock stimuli. Our framework employs a Bayesian approach, emphasizing the significant role of microstructures – comprising PETN energetic grains and HTPB polymer binders with diverse spatial arrangements of porosities – in influencing PBX's SDT behavior. We assess key microstructural factors, including void properties, shape, orientation, and volume fraction, against safety and ignition metrics like run distance and shock pressure. The process involves generating synthetic microstructures to identify candidate structures, followed by quantifying, and reducing the dimensionality of these structures using two-point correlation functions and Principal Component Analysis. Then we apply an active learning algorithm to a Multi-Output Gaussian Process Regression model to enable us to explore structure-property relationships more efficiently and with fewer simulations, thereby advancing our understanding of PBX sensitivity under varying conditions.

Our results demonstrate the framework's ability to identify key attributes influencing SDT behavior in PBX. We found variations in sensitivity based on void shape and volume fraction in the microstructure. For instance, microstructures with a combination of spherical and ellipsoidal or plate-like voids exhibit lower shock pressure and higher run distance responses compared to those with only spherical voids.

Our study, characterized by its batch active learning component, plays a pivotal role in optimizing simulations to maximize information gain while substantially reducing the costs associated with physics-based simulations. It adeptly navigates through complex microstructural variations, guiding simulations to enhance precision in predictions and minimize computational overhead. This not only yields a deeper understanding of PBX microstructures but also establishes new benchmarks in material design for a wide range of engineering applications. The framework's flexibility and practicality make it an asset across various engineering domains, changing the way materials are designed and understood.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIRELESS INTELLIGENT SENSOR ECOSYSTEM (WISE): AN OPEN-SOURCE FRAMEWORK FOR COST-EFFECTIVE STRUCTURAL HEALTH MONITORING

Jordan Kooyman[1], Andrew Bryan[1], Andrew Holm[1], Lucas Wilkerson[1] and Ali Ozdagli[1]*

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ABSTRACT

This paper introduces the Wireless Intelligent Sensor Ecosystem (WISE), an innovative open-source framework designed for managing low-cost sensors to enable cost-effective Structural Health Monitoring (SHM). With the increasing challenges faced by the US infrastructure, this project addresses the need for efficient and affordable monitoring solutions. WISE integrates low-cost smart sensors with open-source software, leveraging advancements in civil infrastructure monitoring. The framework utilizes ESP32, a low-cost, low-power microcontroller platform with integrated Wi-Fi and Bluetooth capabilities. Coupled with a high-quality industrial-grade low-cost inertial measurement unit and an affordable GPS module, the smart sensor platform can collect precise time-stamped data for SHM purposes. The addition of the GPS module also allows multiple sensors connected to the framework to be time-synchronized and enables accurate modal analysis for feature collection and damage detection. The sensor platform is also versatile in supporting various sensor data types such as humidity, temperature, etc. Additionally, the platform can function as an edge device by running TensorFlow models for machine learning-based damage detection algorithms, ensuring early detection of structural issues if required. The raw data collected by the smart sensor platform undergoes an open-source pipeline, including (i) InfluxDB for efficient storage of time series data obtained from the sensor platform; (ii) Grafana, a dynamic and interactive visualization tool providing charts, graphs, and alerts for SHM; and (iii) Node-RED for streamlined sensor management. This integrated system enables real-time storage, visualization, and management of SHM data. Lastly, users can simultaneously manage the status of multiple connected sensors through this framework, for example, starting and stopping data recording, monitoring the quality of service and other metrics. To enhance community engagement, the project shares its source code on GitHub, fostering collaboration and knowledge exchange.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SHORT-TERM MEMORY KALMAN FILTER-BASED DATA FUSION METHOD USING INTERMITTENT-DISPLACEMENT AND ACCELERATION WITH TIME-VARYING BIAS

Ashish Pal[1] and Satish Nagarajaiah[1]*

[1]Rice University

ABSTRACT

Damage detection and system identification techniques utilize structural responses such as acceleration and displacement to infer the structural properties. Displacement measurement contains crucial information that can be useful for drawing meaningful inferences on damage and structural properties. The displacement is often measured using sensors that provide a lower sampling rate as compared to accelerometers. To overcome this limitation, multi-rate Kalman filtering methods have been used to obtain high-frequency displacements by fusing high-frequency acceleration and low-frequency displacement measurements. Often, the recorded acceleration data contains a bias that causes drifts in the estimated displacement. In this study, a short-term memory Kalman filter method has been proposed that contains past realizations of displacement and velocity, and bias terms in the state vector. The state-space equation is formed by linking the displacement, velocity, and acceleration using the finite-difference scheme. By including the bias terms in the state vector, the time-varying bias in the measured acceleration signal can be obtained which is used to eliminate the drifts in the displacement and velocity estimates. The use of memory of states allows measurement updates at each time step which makes it an online method to obtain smooth and accurate state estimates. The proposed method when tested on measured accelerations containing constant, linear, and parabolic bias provided accurate estimates of displacement and velocity irrespective of the shape and magnitude of the time-varying bias. The proposed method applied to three types of oscillators subjected to three different ground motions provided accurate estimates for all cases, especially for the stiff oscillator. The novelty of this study is in introducing the state memory and additional bias term in the state vector which provides accurate smooth displacement and velocity estimates by removing the time-varying bias in the measured acceleration in an online manner, which can be useful for real-time health monitoring purposes.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HIGH VELOCITY IMPACT USING THE TAYLOR TEST

Katie Bruggeman[1]*, Showmik Ahsen*[1]*, Henry Young*[1]*, John Hansen*[2] *and Anthony Palazotto**[2]

[1]*Wright State University*
[2]*Air Force Institute of Technology*

ABSTRACT

Anthony Palazotto
Air Force Institute of Technology

An experiment has been performed at the Air Force Institute of Technology using their Taylor test facility. The Taylor test is an experimental system allowing high-velocity projectile movement into a rigid plate. The idea was to evaluate a specimen's design with varying materials and record their high strain rates through their collision. In this set of tests, IN 718 was being compared at a velocity of 151m/s against a 1 ½ inch thick steel plate. The velocity was recorded by a photographic camera system obtaining photos at a range of 28000 frames per second. Two types of specimens were considered, one made from ½ "x 2" heat-treated extruded IN 718, and the other additively manufactured (AM). It was found that the strain recorded between the two was quite different based on their Modulus of Elasticity. The density of the two types of specimens was very close giving a mass of equal quantity, but due to the moduli the strain and strain rates differed. The stress also differed. Stress values were based on the momentum reached in the experiment and became a function not only of the velocity but also the product of the modulus of elasticity and density. A major issue in the experiment turned out to be the aerodynamics. In certain cases, it was found that the projectile was greatly affected by the initial system support. Specific frictional restraint could produce erratic behavior of the small specimen. To overcome this, attention was directed to reducing the surface.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING THE INTEGRITY AND GAS PERMEABILITY OF POLYVINYL ALCOHOL (PVA) FIBER REINFORCED MORTAR FOR OIL AND GAS WELL DECOMMISSIONING

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[1]University of Southern California

ABSTRACT

The cementitious plug is a crucial part of the decommissioning of oil/gas wells to prevent leakage after the abandonment of the wells. The leakage of gas through cementitious compositions might lead to environmental pollution and economic loss. In the United States alone, an estimated 300 tons of methane, equivalent to 9000 tons of CO2, are released annually from abandoned wells. With the rising use of horizontal drilling and hydraulic fracturing in unconventional resources, the quality of these plugs demands greater attention. In this study, an alternative material for oil and gas well decommissioning is proposed: Polyvinyl alcohol (PVA) fiber-reinforced mortar with a water/binder ratio of less than 0.25. This material aims to mitigate the leakage from abandoned wells. The study evaluated six types of hardened cementitious plugs for their compressive strength, gas permeability, and drying shrinkage. Additionally, scaled-down test specimens simulating the cement plug within the casing were prepared. The research assessed the shear bond strength and gas permeability between the cementitious plug and steel pipe under different curing conditions. Results indicated that the PVA-reinforced mortar exhibited a compressive strength three times higher than that of conventional cementitious plugs and demonstrated significantly lower gas permeability by two orders of magnitude. The shear bond strength and gas permeability between the PVA-reinforced mortar and steel pipe interface were found to be influenced by curing conditions. Specifically, when specimens were cured at T=23°C and RH=100%, the bonding strength of the PVA-reinforced mortar surpassed the conventional plug by more than 20%. However, at temperatures $T \geq 60°C$, the bonding strength of the PVA-reinforced mortar dropped to 60% of that of the conventional plug.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PROBABILISTIC FLOOD RISK ASSESSMENT FRAMEWORK FOR ROAD NETWORKS

Pranavesh Panakkal[1] and Jamie Padgett[1]*

[1]Rice University

ABSTRACT

Assessing road network resilience against disruptions due to urban flooding is essential for promoting community resilience and roadway safety. Existing studies are typically scenario-based and deterministic, with minimal consideration for pluvial floods and spatiotemporal rainfall patterns. Consequently, they fail to fully characterize flood risk to road networks and inform risk mitigation decision-making. This study addresses this need and proposes a probabilistic framework for assessing road network resilience against flood disruptions. The proposed framework couples several realizations of spatiotemporal rainfall events compatible with the study region with a calibrated and validated rainfall-runoff model to generate spatiotemporal inundation data. Flood inundation data are then used to assess the probability of roadway flooding at the link level and connectivity loss risk to essential facilities such as hospitals at the network level. A case study application of the proposed framework will be presented for a select watershed in Houston, Texas, to demonstrate the methodological approach. This study will advance the current state-of-the-art in probabilistic flood risk assessment for road networks under pluvial and fluvial flooding. Specifically, it offers communities a comprehensive method to assess flood impacts on roadways and inform risk mitigation decision-making to enhance community resilience. The contributions of this paper are timely, considering the potential increase in flood risk to urban road networks is an epoch of climate-exacerbated flood hazards.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NONSTATIONARY STOCHASTIC MODELS FOR STRUCTURAL RELIABILITY ANALYSIS IN THE CHANGING CLIMATE

Mahesh Pandey[1] and Sophie Mercier[2]*

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ABSTRACT

A rapid pace of climate change is now becoming evident by a marked increase in the frequency and intensity of weather extremes, and this trend is expected to continue with an increase in global warming in the coming decades.In recent years, a dramatic increase in extremes of heat waves, droughts, rainstorms, hurricanes, and wildfires in many parts of the world has been attributed to climate change effects. Increasing severity of weather events is threatening the safety and operability of existing infrastructure systems and adding the burden of their costly repair and renewal.
Current infrastructure design codes and standards are based on the assumption that climate-induced loads are stationary, i.e., their occurrence pattern and intensity do not change with chronological time. These stationary load models are also used in the reliability-based calibration of design code. Since climate change is causing temporal variations in the frequency and intensity of weather events, it is necessary to develop non-stationary models of these load processes to account for the impact of climate change on reliability of infrastructure systems.

The paper presents nonstationary stochastic processes, namely, the non-homogeneous Poisson process (NHPP) and the linear extension of the Yule process (LEYP), for modelling non-stationary processes. The maximum load distributions are derived and applied to the computation of structural reliability. In the paper, explicit expressions have been derived for the return period, a traditional measure of reliability that is commonly used in the design of infrastructure systems. Unlike the stationary climate, the return period between extreme events would continue to decrease as climate change effects would become more pronounced in the future. It is shown that the LEYP is a more versatile model than the NHPP, as it can incorporate dependence among extreme events occurring over time.

Examples presented in the paper demonstrate that a modest degree of statistical dependence among events leads to a significant reduction in the return period, i.e., a remarkable increase in the frequency of extreme events. Therefore, existing design codes would need to be revised to accommodate such non-stationary changes to ensure a high level of safety of infrastructure systems in the changing climate.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FINITE ELEMENT MODEL OF FAULT ZONE OF NORTHEAST JAPAN SUBDUCTION ZONE FOR DEEP EARTHQUAKES.

Ashay Panse[1] and Craig Foster[1]*

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ABSTRACT

The mechanisms involved in deep earthquakes have been a puzzle for many decades. These types of earthquakes occur at about 300 km or more below the earth surface and have been responsible for great damage and many casualties. We are building a finite element model of subduction zone of Northeast Japan, which extends to about 800km deep. In this model, we simulate the movement of the oceanic (Pacific plate) and continental (Okhotsk plate) plates.

To obtain the proper initial conditions, we employ a model taking into account the viscoelastic behavior of the mantle. The viscoelastic model includes both steady-state and transient power-law dislocation creep, using a BurgerÕs model. To approximate the initial conditions, the geometry and temperature are set up initially, and then gravity is applied. The model is allowed to relax using a small strain assumption, i.e. not updating the geometry, to obtain the initial state. The model is then run forward to examine the evolution of deformation, stress, and material state over time.

Phase transformation of olivine minerals to spinel in the subducting plates, a possible mechanism driving deep earthquakes, is incorporated into the model. Simulations are run to see if the phase transformation could generate earthquakes. Both bulk phase transformation and phase transformation ln narrow bands may occur. The former is modeled using a rate process and is upscaled from single crystal models. In the model, we will check to see under what conditions localized transformation may occur. Eventually, an enhanced element for propagating fracture will be incorporated into the model to simulate slip. The models will be used to examine deep earthquakes and compare with observed magnitudes and recurrence patterns

ACCELERATING THE ANALYSIS OF NON-LOCAL GRADIENT DAMAGE PROPAGATION WITH A NEW FORMULATION OF I-FENN BASED ON TEMPORAL CONVOLUTIONAL NETWORKS

Panos Pantidis[1], Diab Abueidda[1] and Mostafa Mobasher[1]*

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ABSTRACT

Machine-learning models have already shown their promising potential in the field of computational mechanics, but they face several shortcomings that still prevent them from becoming standalone solvers. In view of the above challenges we recently proposed I-FENN, a hybrid framework where Neural Networks (NNs) are directly deployed within the Finite Element Method (FEM) as approximators of the solution of governing PDEs. The key idea of I-FENN is to decompose the problem such that a pre-trained NN predicts one physical state variable, and then the prediction is integrated within a generic FEM solver to compute the remaining state variables like a typical user-defined material model. This iterative process is repeated until the system residuals have converged, abiding therefore with the long-standing practices in the field and ensuring the accuracy of the numerical solution. In our previous work we demonstrated how I-FENN can simulate individual time-snapshots of non-local gradient damage. Here, we present for the first time a new formulation of I-FENN which can successfully simulate the entire load history analysis of non-local gradient damage propagation. First, we adopt a Temporal Convolutional Network (TCN) to capture the history dependence of nonlocal strain in a coarsely meshed domain. We then explore a data-driven vs physics-informed training setup, and we propose a systematic way of feature scaling and output un-scaling to enhance the training efficiency. We finally integrate the trained TCN within the nonlinear FEM solver using either a full or a modified Newton-Raphson scheme, and we apply I-FENN on a fine mesh idealization of the investigated topology. We note that very strict convergence criteria are satisfied across all the increments of the simulation, thus ensuring the solution robustness. Our results demonstrate for the first time the ability of I-FENN to simulate accurately the load history of damage propagation, and we show that I-FENN is 10% - 60% faster than conventional FEM solvers (monolithic or staggered schemes), depending on the problem under consideration.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMAL LIFE-CYCLE ADAPTATION UNDER CLIMATE CHANGE

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ABSTRACT

Various climate change effects pose increasing risks to the nation's infrastructure. Existing approaches for managing climate-related implications typically employ a risk-based, cost-benefit analysis that evaluates a comprehensive set of mitigation strategies against a wide range of simulated possible future scenarios. However, due to substantial uncertainties inherent in climate projections present over the future planning horizon, such cost-benefit strategies often lead to less informed management policies that might be optimal in an average sense, over the mean of anticipated future scenarios, but cannot offer optimal adaptive solutions based on the actual climate effects evolving in time. To address this challenge, we instead formulate climate risk management as a dynamic decision-making problem within a closed-loop stochastic control-based framework using Markov Decision Processes (MDP), taking real-time data into account for evaluating the evolving conditions and selecting the best possible life-cycle actions in time [1]. By adopting the approach in [1], decision-makers can proactively address the evolving climate challenges and can make well-informed, adaptive decisions tailored to the actual climate trajectory at the specific location of interest. The developed framework is illustrated here through a coastal example, relevant to storm surge and sea-level rise hazards, considering also various forms of nature-based solutions. The framework additionally integrates the related environmental impacts of carbon emissions and uptake by employing the social cost of carbon, offering a holistic approach that addresses both the economic and environmental dimensions of coastal flood protection. The policies recommended by the proposed framework are associated with global optimality guarantees and consistently outperform the static cost-benefit baselines under consideration. To summarize, this study makes the following significant contributions to the planning of climate-change-related risk mitigation:

1. Provides a formal dynamic framework for sequential decision-making where decisions made today consider opportunities for future actions, non-stationary changes in climate, and economic growth.
2. Considers environmental impacts as components of the cost model, to illustrate the effect of carbon emissions and uptake on the decision-making process.
3. Illustrates various green or nature-based solutions as potential flood risk mitigation measures and shows their effects in mitigating carbon emissions.

[1] Ashmita Bhattacharya, Kostas G. Papakonstantinou, Gordon P. Warn, Lauren McPhillips, Melissa M. Bilec, Chris E. Forest, Rahaf Hasan, and Digant Chavda. 2024 in review. Optimal Life-Cycle Adaptation of Coastal Infrastructure under Climate Change.

ARGOS: REVOLUTIONIZING BRIDGE BEARING MONITORING WITH A COMPUTER VISION-BASED SYSTEM AND CLOUD COMPUTING

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ABSTRACT

Bridge bearings, vital for supporting superstructure loads, require rigorous safety maintenance against environmental and seismic impacts. Traditional monitoring methods, involving Linear Variable Differential Transformers (LVDTs) and data acquisition devices, are costly and power-dependent, necessitating frequent site visits for data collection and processing. This paper introduces an innovative approach: a computer vision-based bridge bearing monitoring system integrated with an LTE network for real-time data transfer and cloud server processing. We have developed 'ARGOS,' a low-power, vision-based data acquisition hardware, and accompanying cloud-computing resources that process images to extract and record 3D displacements in a database. This system was deployed for a nine-month period and successfully validated on a major highway expressway in South Korea. Our findings demonstrate the efficacy of this novel system in providing efficient, cost-effective, and accurate monitoring of bridge bearing.

This research was supported by four funding sources including the National R&D Project for Smart Construction Technology (Grant RS-2020-KA156887; RS-2020-KA156007) funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure, and Transport and managed by the Korea Expressway Corporation;

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

QR SENSOR: A CITIZEN-ASSISTED, QR-BASED SENSORY DATA ACQUISITION AND CLOUD COMPUTING APPROACH FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

Maintaining the safety of infrastructure is vital for sustainable development in urban areas. Structural aging significantly affects the functionality of urban networks, demanding substantial resources and labor for maintenance. This paper introduces an innovative, cost-effective approach for infrastructure maintenance and monitoring, designed to enhance the functionality of urban networks and ensure public safety. We present a low-power data acquisition system coupled with a rapid data visualization method for precise structural response measurement. Our sensor, attachable to any structure, measures acceleration, tilt, and strain, functioning for three years without the need for battery replacement. Data collected over preset periods are compressed into QR codes, easily scannable by citizen volunteers. These codes, captured via smartphones, are processed using cloud computing for data accumulation and analysis in a centralized database. The system's effectiveness has been validated through long-term monitoring of a pedestrian bridge, previously deemed structurally deficient, thus proving its utility in enhancing urban infrastructure maintenance and public safety.

This research was supported by four funding sources including the National R&D Project for Smart Construction Technology (Grant RS-2020-KA156887; RS-2020-KA156007) funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure, and Transport and managed by the Korea Expressway Corporation;

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION ON INTERFACIAL TRANSITION ZONE OF CONCRETE

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ABSTRACT

Characteristics of the interfacial transition zone of concrete are essential because it significantly affects concrete properties such as strength, permeability, durability, and others. To quantify and validate the interfacial fracture resistance between aggregate and cement paste, three point-bending tests are performed using three configurations, i.e., full mortar specimens, half-mortar and half-aggregate specimens, and mortar specimens with a cylindrical aggregate inclusion. The fracture energy of mortar is measured using the full mortar specimens, while the interfacial fracture energy is measured using the half-mortar and half-aggregate specimens. The measured interfacial fracture energy is approximately 10% of the mortar fracture energy in this study. Based on the measured fracture energies, the three-point bending test with the mortar specimens with a cylindrical aggregate inclusion is simulated using the cohesive zone modeling. The computational result agrees well with the experimental result, which confirms the validity of the measured interfacial fracture energy.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNSUPERVISED STRUCTURAL DAMAGE ASSESSMENT USING IMPROVED DEEP ONE-CLASS ANOMALY DETECTION

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ABSTRACT

The recent development in deep learning has significantly advanced vibration-based damage detection in civil infrastructures. Traditionally, such methods rely on supervised learning, needing large datasets covering normal and damaged conditions. However, acquiring datasets for damaged structures is challenging, especially in real-world applications. To overcome this, this study investigates the feasibility of unsupervised deep one-class classification approach that uses only data from the undamaged state of structures. The proposed framework starts by using the Fourier Synchrosqueezed Transform (FSST) to extract time-frequency characteristics of vibrational responses. A new scaling process is herein applied to the FSST values for highlighting the differences in time-frequency characteristics according to damage presence. This scaled time-frequency information is then fed into a two-dimensional deep autoencoder (2AE), which includes consecutive encoder and decoder with convolutional neural network layers. The 2AE model is exclusively trained on intact state data only, resulting in high reconstruction accuracy for normal data and lower accuracy for damaged data. In this regard, damage scores are measured using the Root Mean Square Error (RMSE) between the reconstructed and original time-frequency images. The threshold for damage detection is set at the three-sigma limits of RMSE for intact states. To validate our approach, we first simulate a 9-story shear building subjected to random excitation, introducing damage scenarios by reducing the stiffness of structural members on specific floors. The results demonstrate the high accuracy of the proposed framework in damage detection, with near-perfect detection rates of 99.8% to 100% for damage degrees of 0.5 and above. Finally, we apply the framework to field monitoring data collected from actual damaged truss bridges. The trained 2AE model, using only intact datasets, successfully identifies instances of damage in truss members without the need for specific damage datasets or a labeling process. It is noted that (1) the sensor closest to the damaged member demonstrates the highest damage score, and (2) the damage score somehow correlates with the severity of the damage. These findings substantiate the applicability of the proposed framework for both damage detection and localization.

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTATION OF ATOMIC LEVEL EIGENSTRAINS CONJUGATE TO ATOMIC LEVEL RESIDUAL STRESS

Kehinde Omotayo[1], Mohammad Amin Hodaei[1], Ranganathan Parthasarathy[1], Anil Misra[2] and Lizhi Ouyang[1]*

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ABSTRACT

Atomistic simulations including classical molecular dynamics simulations are often used to investigate the underlying mechanisms behind phenomena such as stress corrosion cracking, shear transition initiation in disordered materials such as metallic glasses, hydrogen embrittlement of steels, and inform the next hierarchical scale in multiscale modeling of these phenomena. Per atom definitions of stress and strain plays an important role in coupled FE/MD simulations and in the determination of residual stresses in structural components. Residual stress can be classified into macro-scale Type I stresses averaged across grains, intra-granular Type II stresses, and Type III atomic level stresses. While the influence of Type I macro-scale residual stress on mechanical failure has been widely established and is being used to develop phenomenological models, a study of Type II and Type III residual stresses is required for a physically-based theoretical understanding of multiphysics phenomena and the eventual development of multiscale models. While there has been a great deal of research in the determination of Type I residual stresses from various destructive and non-destructive methods, the same cannot be said for Type II and Type III residual stresses. This work focuses on the development of a novel method for accurate determination of atomic level strains and Type III residual stresses from classical molecular dynamics simulations for eventual application to multi-physics problems. Atomic level stress is completely defined in a material when the positions of all atoms are known. The time-averaged stress per atom is zero only when an atom is in its ideal lattice position in a perfect crystal. Accordingly, to establish a one-to-one correspondence between classical continuum modeling and classical molecular dynamics simulations for internal stress and strain calculation in defective crystals, the reference state for calculation of atomic level strain should be the perfect crystal. For the example of residual strain around a vacancy in fcc Aluminum, the local atomic level strains calculated without inclusion of the vacancy atom in the reference state have been found to be too small in magnitude to result in the observed per atom stresses in the nearest neighbors. Furthermore, determining the complete values of the local strains and their decomposition into elastic and inelastic components is a non-trivial problem. Atomic positional covariances resulting from thermal vibration are demonstrated to be of use in calculating elastic components of local strains. The method is practically relevant since thermal ellipsoids can be computed from X-ray and neutron diffraction spectra.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-PHYSICS MODEL UPDATING OF A JACKET OFFSHORE WIND TURBINE USING MEASURED VIBRATION DATA

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[1]Tufts University

ABSTRACT

In 2020, the US set a target to install 30 GW of offshore wind by 2030. In addition to the 30 GW target, the US Department of Energy is funding research to install 15 GW of floating offshore wind by 2035. The design of new offshore wind farms can benefit from studying the current OWTs' health conditions and the effect of the environment on their operation. In this regard, we study the health condition of an existing Haliade 6-MW jacket-supported offshore wind turbine (OWT) located at the Block Island Wind Farm (BIWF). Physics-based models such as finite element (FE) models are often used in the structural design, condition assessment, and response prediction of the OWTs. Although FE models are considered high fidelity, some discrepancies are often observed between the model predictions and actual data measurements from the real structure. Part of the differences between the FE model and data can be attributed to uncertainties in the model parameters. Uncertainties in the model parameters and the modeling approach can be minimized by predicting the key parameters of the OWT. Our model updating process reduces the model parameter uncertainty by minimizing the differences between the FE model and the measured data through an optimization procedure. In this study, we update the multi-physics model of the BIWF-OWT in the OpenFAST tool based on measurement data obtained from an instrumented turbine. The stiffness and damping of an OWT are affected by a change in environmental and operational conditions. To adjust the OWT model's stiffness and damping, the structural, aerodynamic, hydrodynamic, soil dynamic, and controller parameters are updated. The target parameters are wind speed and direction, rotor speed, yaw error, and aerodynamic parameters such as lift distribution at the outboard of the blade. The structural parameters are blade mass, blade center of mass, blade flapwise stiffness, nacelle center of mass, nacelle mass, and substructure stiffness.

Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC CONVOLUTIONAL NEURAL NETWORKS FOR SURROGATE MODELING AND UNCERTAINTY QUANTIFICATION IN SOLID MECHANICS

George D. Pasparakis[1], Michael Shields[1] and Lori Graham-Brady[1]*

[1]*Johns Hopkins University*

ABSTRACT

Stress field prediction and material deformation are one of the key tasks in the field of computational mechanics. They are typically provided by means of Finite Element Analysis (FEA), which can become computationally prohibitive considering complex microstructures and material behavior. Such a limitation is especially important within the context of structure–property exploration and inverse design for materials discovery where a larger number of model evaluations is required. Recently, the advent of data-driven methods has directed attention towards machine learning (ML) techniques as cost effective FEA surrogates in materials applications. Despite the large body of work, the majority of ML approaches is either limited to low-dimensional (vector valued) problems and/or does not provide uncertainty estimates in the predictions. In this regard, building upon previous results at the intersection between solid mechanics [1] and data-driven materials modeling [2], this work proposes a framework for stress field prediction and uncertainty quantification for diverse materials microstructures. First, a modified U-Net [3] neural network (NN) is employed to provide a data-driven image-to-image mapping. Next, aiming at quantifying the degree of confidence in the predictions, the NN parameters are treated as random variables in a probabilistic setting. Specifically, the posterior of the parameters with respect to the data is estimated by considering three state-of-the-art algorithms which are relevant to uncertainty quantification (UQ) in deep learning: the Monte-Carlo Dropout [4] technique, the Bayes by Backprop [5] algorithm and the Hamiltonian Monte Carlo [6] method. These Bayesian deep learning techniques are amenable to large scale convolutional neural network applications and estimate the posterior distribution with varying levels of approximation. A systematic comparison of the efficacy of these methods is performed by considering a fiber reinforced composite system as well a polycrystalline material application. It is shown that the proposed methods yield predictions of comparable accuracy to FEA but also offer interpretable uncertainty estimates in the predictions.

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Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COUPLING FORM-FINDING AND BUCKLING ANALYSIS FOR GRIDSHELL DESIGN

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ABSTRACT

Gridshells span long distances with slender cross-sections due to their mechanically efficient shapes, which allow them to bear external loads mainly through compressive membrane action. Form-finding methods generate such funicular shapes based on the principles of static equilibrium. Buckling is a nonlinear mechanical phenomenon that often governs the design of slender structures subject to compressive forces, but most form-finding methods exclude it in their numerical calculations. As a result, these methods generate funicular but potentially unstable shapes. In this work, we introduce an approach to automate the design of buckling-resistant gridshells via gradient-based optimization. The proposed approach combines form-finding and buckling analysis with automatic differentiation. This combination enables the concurrent optimization of the global geometry and the cross-sectional properties of the structure. Our findings illustrate how the simultaneous exploration of both form and material design spaces opens up opportunities to design gridshells that are both lightweight and less prone to buckling.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SURROGATE MODELS TO CAPTURE THE INFLUENCE OF NEIGHBORING STRUCTURES ON HYDRAULIC DEMAND MODIFICATION

Jainish Maheshbhai Patel[1] and Jamie Padgett[1]*

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ABSTRACT

Potential hydraulic demand modifications caused by the presence of neighboring structures during hurricane storm surge-wave events are often ignored while performing risk assessment of coastal infrastructure. Since many coastal infrastructures (e.g., residential structures, industrial complexes) may be densely distributed, ignorance of such effects could lead to errors in estimating the damage potential of structures within a coastal portfolio. Addressing existing drawbacks, this study focusses on developing a surrogate model for estimating hydraulic demands on structures considering the presence of surrounding structures. Beyond gleaming insight on spatial proximity of neighboring structures and wave parameters, such a model paves a path for subsequent fragility and risk modeling. A group of aboveground storage tanks (ASTs) in a refinery facility is considered as a case study infrastructure, given their typical layouts in tank farms. The hydrodynamic loads acting on a tank are estimated numerically through full-scale computational fluid dynamic (CFD) analysis performed using commercial finite element software LS-Dyna. Considering the uncertainties associated with storm-surge-wave parameters, tank geometry, and relative position of tanks, statistical sampling is performed to cover a wide range of parameter combinations. This dataset is used for training the statistical learning model to develop a parameterized hydraulic demand model. The results highlight the structural shielding and flow channeling effects due to reflection, refraction, and diffraction phenomenon of storm surge-wave propagation due to the presence of surrounding structures. The proposed parameterized demand model can be used to efficiently estimate hydraulic demands on individual tanks considering the effects of neighboring structures to improve damage and risk modeling. The proposed framework can also be extended for other types of infrastructure systems where spatial proximity effects influence observed damage patterns but have yet to be captured in regional risk and resilience models.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING OF TRIAXIAL STRESSES AND STEEL REINFORCEMENT-INDUCED TRANSVERSE CONFINEMENT IN CONCRETE DAMAGED BY ALKALI-SILICA REACTION

Madura Pathirage[1], Tianjiao Gai[2], Boqin Zhang[3] and Gianluca Cusatis[2]*

[1]University of New Mexico
[2]Northwestern University
[3]Georgia Institute of Technology

ABSTRACT

Alkali-silica reaction (ASR) is one of the leading causes of deterioration in many existing structures. ASR is a slow-evolving chemical reaction occurring inside concrete. Alkali ions, mainly provided by cement, react with amorphous silica or certain quartz contained in reactive aggregate to form the so-called ASR gel. In a high humidity environment, this gel swells due to water imbibition, and by osmotic pressure generates expansion and micro- to macro-cracking. When it comes to actual ASR-affected structures, the effect of multi-axial confinement on the ASR process and the induced damage is of paramount importance. Two main sources of confinement are typically identified: (i) externally exerted mechanical stresses and (ii) the presence of longitudinal and transverse steel reinforcements. This presentation aims to summarize the research effort and work performed in the recent years by the authors on the modeling of ASR, especially on the effects of confining pressures on the mechanical properties of ASR affected plain and reinforced concrete. The computational framework includes fully calibrated and validated models for moisture diffusion, heat transfer, cement hydration and aging, thermal expansion, creep, and shrinkage, in combination with the robust Lattice Discrete Particle Model (LDPM), which simulates concrete internal structure at the mesoscale defined as the length scale of coarse aggregate pieces. Numerous simulations and comparisons with experimental data produced by the authors and gathered from the literature are discussed. The capabilities of the overall computational model in capturing experimentally observed key features are demonstrated and include the transfer of expansion in the transversal unrestrained direction with cracks having a preferential direction in the restrained direction, the evolution of mechanical properties in time for different confinement configurations, and the effects of longitudinal and shear reinforcements on the induced-transverse confining stresses and the resulting load-bearing capacity of reinforced concrete beams. Finally, the limitations of the model are discussed for future improvements.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A CROSS-SCALE NEURAL NETWORK ASSISTED POWDER DYNAMICS MODEL FOR ADDITIVE MANUFACTURING PROCESSES

Shashwot Paudel[1] and Jinhui Yan[1]*

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ABSTRACT

Additive manufacturing (AM) has come forward as a cornerstone of modern industrial production. In the present realm of additive manufacturing processes, based on how the powder delivery is done over the substrate during the laser scanning process, two methods have been predominant - laser powder bed fusion (LPBF) and directed energy deposition (DED). The comprehensive goal of our research is to develop a reliable cross-scale powder dynamics model for these AM processes. Regardless of the widespread use in research and industries ranging from aerospace to medicine, LPBF and DED still face significant challenges in optimizing the powder behavior which has a direct impact on the efficiency of these processes and the quality of the manufactured products.

This work specifically aims to address challenges in the case of LPBF experiments through an innovative approach that incorporates computer vision (CV) assisted neural network with two-way coupled Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) simulations. This combination significantly reduces the computational costs associated with any high-fidelity powder-scale simulations by directly utilizing detailed powder-scale spatter information parameterized using a neural network that feeds on data from an extensive range experiments while significantly improving the accuracy of the simulations. The experiments are designed based on a set of controllable process parameters such as laser scanning speed, laser power, chamber gas type, and laser scanning direction.

The application of neural networks to process CV generated powder scale information allows for faster simulations with more dynamic and accurate powder behavior prediction under varying manufacturing conditions. This enables us to predict and address potential defects that might arise from any sub-optimal powder spatter behavior. In addition to the optimization of existing LPBF techniques, this model can also help develop more efficient and reliable manufacturing strategies and even optimize the design of AM chambers.

In summary, with the incorporation of computational innovation and development in recent years together with practical experimentation, this current model builds over basic theoretical research and hopes to demonstrate reliable applications in real-world manufacturing scenarios.

Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NON-LINEAR MODELLING OF MULTI-LAYERED RANDOMIZED ARCHITECTED MATERIAL (MLRAM) UNDER TENSILE LOADING FOR A TENSEGRITY STRUCTURE

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ABSTRACT

Architected materials allow engineers to design and develop materials with desired properties through interplay of geometry. Recent research works shows the applications of architected material in the areas of Cubic-Bravais lattice and crystal microstructures. It also provides an opportunity to investigate behavior of micro-scale structures at a macro-scale. A newly developed Multi-layered Randomized Architected Material (MLRAM), inspired by polymeric structures, has a potential to act as damage detection indicators in highly redundant structures such as tensegrity structures [1]. MLRAM can be incorporated in tension members of a structure that can help monitor and visually detect damages. This will reduce the use sensors in in the field of health monitoring. The geometrical design of MLRAM is harnessed through Latin Hypercube Sampling. MLRAM specimens are 3D printed using Stratasys Objet500 Connex3 printer with Vero Cyan as the printing material. Experiments are conducted to obtain the tensile properties of this newly developed material. The behavior is analyzed based on the parameters of coordination number and percentage density of Long Links. This study presents a computational model that captures the tensile behavior of MLRAM using a non-linear finite element method. A framework is created which captures the progressive failure of the links of the MLRAM. The tensile behavior is obtained automatically by following the algorithm presented by the framework and is achieved by combining models developed using Matlab and Abaqus. The experimental and computational results are validated. Further, this model is used to obtain the tensile behavior of MLRAM for various randomized geometries. The variation of stiffness, peak tensile capacity and post peak behavior of the MLRAM under tension is analyzed with respect to its parameters of coordination number and percentage density of Long Links. Results show that variation of stiffness and peak tensile capacity decreases with increase in coordination number and percentage density of Long Links.

Keywords: Architected Material, Non-linear finite element method, Polymer Network;

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Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECONFIGURABLE PARTITION SYSTEM FOR ADAPTIVE MODULAR CONSTRUCTION

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[1]University of Michigan

ABSTRACT

Modular construction has received increased interest in recent years because of its ability to decrease a project's cost and construction timeline. Generally, modular construction lacks adaptability and reusability, making it less resilient to future societal needs. One source of this deficiency is the use of traditional partition walls since they cannot be reconfigured to new floor plans or deconstructed for later use. Here, we propose an adaptable 2-D partition system composed of an adjustable number of cells, where each additional cell increases the variety of possible partition lengths.The system is made of internal "accordions" that allow the external surface of the system to remain flat in collapsed and deployed states and allow it to lock more easily when in a collapsed state. Additionally, this partition wall design has a hollow interior that can be filled with additional components to improve thermal, acoustic, or structural properties of the system. We analyze admissible motions and the kinematic rigidity of the partition wall system in multiple configurations using rigidity theory and contact. These analyses demonstrate that the system can reconfigure as needed and can be made rigid for functional use as a structure. From this analysis, we determined the necessary constraints to transform the system from deployable to rigid. This partition system could have many of the same benefits as traditional modular components, such as being mass-producible and easily assemblable, but would also be adaptable to different lengths, suiting versatile design scenarios. Along with being adaptable, this structure could potentially decrease manufacturing costs because of its chain-like assembly and encourage reusability because of its adjustable components.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHASE FIELD METHOD-BASE MODELING OF WOOD FRACTURE

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ABSTRACT

Wood, as a naturally grown material, exhibits an inhomogeneous material structure as well as a quite complex material behavior. For these reasons, the mechanical modeling of fracture processes in wood is a challenging task and requires a careful selection of numerical methods. Promising approaches like limit analysis or the extended finite element method (XFEM) in combination with microstructure materials models deliver good but not yet satisfying results. Particularly the latter approach, including XFEM, has severe difficulties with crack paths in regions with complex morphology, mainly around knots. Therefore, in this work, the focus is laid on the recently emerging and very popular phase field method [1]. Especially geometric compatibility issues that limit the use of XFEM can be avoided, as the crack is not discretely modeled but smeared over multiple elements. This allows the formation of complex crack patterns, defined by the underlying differential equations and boundary conditions but not restricted by the mesh geometry. The present implementation [2,3] contains a stress-based split which allows proper decomposition of the strain energy density for orthotropic materials. Furthermore, the geometric influence of the wood microstructure on crack propagation is taken into account by a structural tensor scaling the length scale parameter of the phase field [3]. For solving the system of differential equations, a staggered approach with an additional Newton-Raphson loop is used. The developed algorithm was tested on various problems. Compared to XFEM more computation time was needed as the phase field method requires a finer discretization. However, crack patterns, including branching and merging, could be modeled very stable and accurately, even in the vicinity of knots where the material structure of wood is particularly complex and interface zones exist.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL VALIDATION OF REAL-TIME, WEIGHTED CONTROL ALGORITHM ON CIVIL INFRASTRUCTURE

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ABSTRACT

Civil infrastructure is subject to damage from large external loads, such as earthquake and winds. One method of mitigating such effects is to introduce active control techniques which require a seamless integration of information across sensors, controllers, and actuators. To promote information flow, wireless sensor networks have been used as a low-cost alternative to traditional wired sensing and actuation systems. While such networks enable a richer exchange of information between sensors and actuators and enable improved localized control capabilities, they also introduce their own additional challenges such as latency in the communication channel and computational inundation at individual control nodes. This study seeks to alleviate these challenges by employing real-time, front-end signal processing at the sensing node that results in a decomposition of information according to its spectral content. This information is then passed to a control node which can implement a simplistic sum of weighted inputs to calculate a control force that is then communicated to an actuator. This process eliminates complex computations at the control node and promotes real-time control within the system. This proposed control algorithm is experimentally validated through active control of a small-scale, four-story structure subject to seismic base excitation. Results from this control scenario are compared to a more traditional control algorithm, the Linear Quadratic Regulator.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL-LIFE APPLICATION AND CHALLENGES OF MODERN TECHNIQUES AND TECHNOLOGIES TOWARDS A SUPERVISED AUTOMATION OF CONDITION ASSESSMENTS

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ABSTRACT

Condition assessment is a common practice to evaluate the structural performance of assets in the built environment. These condition assessments could be performed as a routine evaluation to identify conditions that could affect the performance of the asset, reduce the structural capacity, and even result in a stop of functionality. In some cases, these assessments are even performed after a major problem has been discovered or occurred (e.g., major water infiltration, partial collapse, spall in a facade component). Typically, performing these assessments is time-consuming and costly, requiring large teams of experts to be involved. Research during the last decades has resulted in advances in automatizing the process of assessing the structure, facade, and roof components. Examples of these advances include the development of multiple techniques, methodologies, and equipment highly oriented on contributing to structural health monitoring, sensing, computer vision, and damage identification, among other related topics. The implementation of novel technology during the condition assessment has facilitated the evaluation of buildings and other structures. For instance, the use of unmanned aerial vehicles (a.k.a. UAVs, drones) for roof inspections has contributed to reducing the extensive campaign inspections. Similarly, robotic frames are used to collect facade photos and combine them into a gigapixel panorama (i.e., ultra-high resolution image) to reduce close-up inspections using industrial rope access techniques and/or suspended scaffold. 3-D modeling and photogrammetry techniques have reduced the number of frequent site visits and facilitated discussions with clients and contractors. Also, 360-degree and borescope cameras are used to evaluate obscured conditions typically behind building finishes and/or inaccessible locations. Another example corresponds to the use of structural response sensors to record such responses in real-time and determine the change in material and geometry properties. The objective of this presentation is to cover some examples of how the use of these technologies has enabled more efficient assessments, the typical pieces of equipment used during the assessments, and their implementation to address real-life issues in the built environment, but also to present some of the challenges that interfere with a full automatization of condition assessment of structures and building envelope components.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISION-BASED VEHICLE AXLE LOAD IDENTIFICATION ON HIGHWAY INFRASTRUCTURES USING SEMANTIC DEEP CLASSIFIER OF VEHICLE COMPONENTS

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ABSTRACT

Traffic load monitoring is a challenging problem in non-intrusive monitoring of highway pavements and bridges taking the advantages of innovative computer vision techniques. Weight distribution induced by different highway vehicle types varies greatly in terms of the number of axles and axle spacings. Therefore, vehicle classification in an axle-based fine-grained level is a vital to perform reliable axle load identification without matched readings from a high-cost WIM or BWIM equipment. In recent years, vehicle classification using deep image classifiers has been applied to group vehicle loads in a coarse-grained level with promising results. However, image-based practices of axle-based vehicle classification lacks in minority accuracy and misclassification interpretability. Various loading conditions from trucks dominate the deterioration of highway infrastructures, while heavy trucks make up only a small proportion of traffic compared to small vehicles. In this approach, a fully convolution network (FCN)-based semantic segmentation learning is proposed to obtain pixelwise classification of vehicle components using input vehicle images captured from highway traffic flows. With a target-free camera calibration, the semantic output masks of individual axles, vehicle power unit, and trailers can be used to obtain measurements of axle spacing(s), vehicle sizes, and vehicle spatiotemporal information. Then, the detected vehicle is classified into a fine-grained level using a decision tree of axle configuration and vehicle height estimation. Finally, Gaussian mixture models of vehicle gross weight (GVW) distributions for each vehicle class are used to identify individual axle loads of the classified vehicle. Accuracy and reliability of the proposed algorithm was validated and evaluated processing a 3-hour video of a two-lane highway traffic flow. A competitive classification accuracy of 98.9% is achieved comparing to the monitoring data of the same traffic flow collected by a local WIM system.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STOCHASTIC SURROGATE MODELING VIA BAYESIAN DEEP LEARNING FOR SEISMIC RESPONSE ESTIMATION

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ABSTRACT

Seismic risk assessment plays a crucial role in engineering decision-making by quantifying the potential negative impacts of earthquakes on infrastructure in a probabilistic manner. However, accurately capturing seismic response with uncertainty often requires computationally expensive repeated nonlinear time history analysis (NTHA) for complex structural models. To address this challenge, stochastic emulators have emerged as effective tools for reducing computational burden by utilizing surrogate models that approximate the mapping of input data to seismic structural responses, enabling fast predictions of seismic response.

Given the high dimensionality of stochastic earthquake excitations, a stochastic emulator seeks to simulate the probabilistic model of seismic response for specific structural configurations, which involves modeling aleatoric uncertainty present in the stochastic sequences. However, establishing a heteroscedastic stochastic emulator requires a considerable number of replication simulations for each training point, leading to substantial computational costs. Recent research has introduced a partial replication strategy that employs Gaussian processes (GPs) to establish the heteroscedastic variance field using only a portion of repeated numerical simulations at a training point.

In this work, we leverage Bayesian deep learning to offer a systematic approach to integrate the powerful learning capabilities of deep neural networks with the ability to model and characterize uncertainty. Recent advancements have shown that it is possible to combine aleatoric and epistemic uncertainties in a Bayesian neural network by incorporating input-dependent variance in the loss function and placing a prior on the weights, respectively. Moreover, efficient Bayesian inference can be achieved through practical techniques such as dropout, which serves as variational Bayesian approximations. Through case study examples, we demonstrate that the proposed approach achieves improved computational efficiency and accuracy by eliminating the need for replications at each training point and accommodating the nonlinear probabilistic distribution of seismic response given specific structural configurations.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRAMEWORK FOR UNCERTAINTY IDENTIFICATION OF BANDGAPS IN KIRIGAMI-BASED STRUCTURES

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ABSTRACT

Kirigami is an ancient art based on paper cutting and folding to create three-dimensional arrangements from two-dimensional sheets. Recently, the usage of this technique in the creation of metamaterials with unconventional mechanical properties has been the focus of many researchers. Some interesting findings have been reported for Kirigami-based substructures with auxetic behaviors, tailored thermal coefficients of expansion, and capabilities for restricting elastic wave propagation through bandgaps. This last effect, highly dependent on the geometrical and inertial properties of the substructure, allows for interesting vibration and acoustic isolation designs.

Nonetheless, it is important to consider the computational demand of studying these macrostructures, mainly when a large number of substructures are employed. Additionally, manufacturing uncertainties should be considered when estimating the elastic wave propagation characteristics. Therefore, the computational demand increases as stochastic techniques for uncertainty propagation, such as Monte Carlo simulations, should be executed to predict the macrostructure's behavior. With that in mind, this research aims to present a framework to speed up the uncertainty quantification in the bandgap estimation for Kirigami-inspired substructures.

In this framework, substructures' mass and stiffness matrices are computed using a nominal set of model parameters and reduced by adopting the Craig-Bampton method. Any deviation from these nominal parameters is considered a perturbation to the baseline configuration. Specifically, the perturbed mass matrix is assumed to be equivalent to the nominal configuration, while the perturbed stiffness matrix is derived by perturbing a nominal stiffness submatrix. This submatrix exclusively contains the natural frequencies of the substructure at a fixed interface. To expedite the estimation of the perturbed stiffness matrix, a Kriging-based metamodel is employed to establish a relationship between model parameters and the aforementioned natural frequencies. By training the metamodel with a small set of model parameters centered around the nominal characteristics, it is possible to obtain the reduced stiffness matrix for a new set of model parameters without the need to rerun the finite element analysis (FEA) facilitating the recursive analysis required within a Monte Carlo Simulation. This framework is illustrated using a simple 2D auxetic Kirigami-based macrostructure and validated through high-fidelity simulations based on FEA.

PHYSICS-INFORMED NEURAL NETWORK FOR MODELING POLYMER MATRIX COMPOSITE MATERIALS UNDER VOLUMETRIC DAMAGE

Min Lin[1], Vincent Petrey[1] and Xiang Zhang[1]*

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ABSTRACT

The Finite Element Method (FEM) has traditionally served as a powerful and versatile tool for solving a wide range of partial differential equations (PDEs), including those from solid mechanics problems. In recent years, machine learning (ML) techniques have emerged as promising alternatives to FEM for solving PDEs. We are particularly interested in the Physics-Informed Neural Network (PINN), which has shown its promise in various scientific and engineering applications. PINN is a type of neural network that combines the strengths of neural networks and physics-based equations and constitutive laws. It involves training a neural network to approximate the solution to a partial differential equation (PDE) by including the loss from governing equations and boundary conditions into the loss function, such that once the neural network is trained, both the boundary conditions and governing equations are satisfied. Since PINN directly learns the solution from data and incorporates the physics constraints during training, it is highly adaptable and can be applied to a wide range of problems without many changes between 2D and 3D formulations. Because of its meshfree nature, it does not require mesh generation or re-meshing, handles complex geometries, and adapts to irregular domains easily, which attracts increasing research interest. However, in the field of computational solid mechanics, PINNs are currently limited to simple linear elasticity and the capability to model the nonlinear time-dependent problems is limited. In this work, we develop a PINN that targets the analysis of the time-dependent response of polymer matrix composite material modeled with continuum damage model (CDM). The constitutive damage model is discretized concerning time, and incorporated into the loss function, together with the PDE loss and boundary loss, to ensure the prescribed damage evolution. To assess the accuracy and efficiency of PINN, we conduct a comprehensive set of numerical experiments on various 3D particulate composite materials by both PINN and direct numerical simulation using the Interface Enriched Finite Element Method (IGFEM). Both the overall stress-strain response and local response over the microstructure are discussed. The trained PINN for a chosen microstructure is also demonstrated to be usable in a multiscale scale setting, to leverage the efficiency of the fully trained PINN. The numerical examples demonstrate the efficiency and accuracy aspects of PINN for modeling composite materials under matrix or inclusion damage and probe its potential in a two-scale modeling setting to replace the finite element-based evaluation.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DECISION VARIABLE-BASED INVERSE DESIGN OF ISOLATED STEEL FRAMES USING GAUSSIAN PROCESS REGRESSION

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ABSTRACT

Conventional earthquake design methodology to target performance metrics and decision variables (DV), such as repair cost or expected downtime, involves iterative processes of choosing preliminary design parameters, modeling and analysis, performance assessment, and fine-tuning until the threshold is met. Moreover, although codified design for higher performance targets exists for fixed-based structure, the inverse relationship from DV to design is much less explored in base isolation applications. The prediction of and design for isolated structures' behavior under design-level ground motions is well-studied, however failure prediction for isolated systems is highly nonlinear during extreme events. Given the difficulty for isolated design for extreme events, high uncertainty is also involved in predicting loss and damage, thus raising the need for metamodels. To bridge the procedure from basic design parameters and DVs, surrogate modeling is sought as an effective metamodel to map a space of design variable combinations to their resulting performance. A database of isolated steel moment resisting frames and concentric braced frames, with varying design parameters, earthquake inputs, and structure configurations is constructed and are subjected to nonlinear time history analysis using OpenSees. The corresponding engineering demand parameter outputs are used to perform probabilistic loss and downtime estimation using the FEMA P-58 framework to estimate building performance. A Gaussian process (GP) model is then utilized to fit a model predicting DVs to the structures' input parameters, and adaptive design of experiment is performed on the dataset to determine supplemental data points needed to reduce prediction variance. The fitted GP model then allows for the performance prediction of the entire considered space of design variables outside of the limited database, and optimization is carried out to identify inverse designs suited to achieve certain performance thresholds, such as 2 weeks' downtime. The completed inverse design framework allows for the immediate identification of an optimal Pareto front of suitable parameter combination. Design variables such as bearing stiffness, required isolation moat gap, and superstructure overstrength needed to achieve the desired repair cost/downtime for structures, subjected to configuration constraints can then be cost-optimized, leading to a better-informed preliminary design.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY QUANTIFICATION FOR MODEL-CONSTRAINED DEEP-LEARNING INVERSE SOLVERS

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[1]The University of Texas at Austin

ABSTRACT

While Bayesian neural networks facilitate uncertainty quantification (UQ) for neural network predictions, the uncertainty is questionable using Gaussian priors on the weights and biases. Such weights and biases are artificial quantities and parameters, and thus Gaussian priors are a matter of convenience rather than rationale.

In this talk we present our attempt to circumvent the issue of an interpretable prior for the weights and biases, along with a concise description of our framework for a UQ-enabled, model-constrained, deep-learning-based inverse solver. To justify our approach we provide comprehensive numerical results in problems for 2D inverse heat conductivity, 2D inverse initial conditions for the time-dependent Burgers' equation, and 2D inverse initial conditions for the time-dependent Navier-Stokes equations.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Machine learning applications in wind engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SURROGATE-BASED CYBER-PHYSICAL AERODYNAMIC SHAPE OPTIMIZATION OF HIGH-RISE BUILDINGS

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ABSTRACT

This study proposes a surrogate-based cyber-physical aerodynamic shape optimization (SB-CP-ASO) procedure for high-rise buildings under wind loading. Three components are developed for the procedure: (1) an adaptive subtractive manufacturing technique, (2) a high-throughput high-frequency base balance (HFFB) wind tunnel testing procedure, and (3) a flexible infilling strategy. The downtime of the procedure is minimized through a parallel manufacturing and testing (llM&T) technique. A building using a setback strategy combined with cross-section modifications (three shape parameters in total) was used to demonstrate the performance of the proposed SB-CP-ASO procedure. A total of 173 physical models were evaluated during the predefined testing window with a balance between performance optimization and global surrogate model accuracy. The adaptive subtractive manufacturing technique was able to rapidly create models with complex building shapes (10 mins on average) using a 7-axis KUKA robotic arm system at the University of Florida’s NSF-NHERI Experimental Facility. The high-throughput testing procedure was able to evaluate 17 models per day on average, equivalent to 25 mins for each model under 10 wind angles. The infilling strategy was able to: (1) return a family of valid design alternatives anytime during the procedure, accommodating shorter or interrupted testing windows, (2) ensure local accuracy at promising regions, and (3) escape from local optima. The SB-CP-ASO procedure provides an efficient platform between owners, architects, and structural engineers to identify ideal candidates within a defined design space for real-world high-rise buildings. In addition to using it as a whole, the three components developed in this study can be individually applied to other studies.

A TOPOLOGY OPTIMIZATION STUDY APPLIED TO STRUCTURAL FOUNDATION DESIGNS VIA THE TOBS-GT METHOD

Kamilla Emily Santos Silva[1]*, Gabriel Vicentin Pereira Lapa*[1]*, Josue Labaki*[2]*, Alfredo Gay Neto*[1]*, Emilio Carlos Nelli Silva*[1] *and Renato Picelli**[1]

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ABSTRACT

This work presents a topology optimization methodology applied to structural foundations under static and dynamic loads. The optimization problem is solved by considering a large region within the ground as the design domain, where the structural foundation is designed to support above-ground tower-like structures. Within the design domain, the available materials are interpolated, and each one of them is defined by a binary design variable, being either concrete (variable 1) or soil (variable 0). The employment of binary variables establishes a distinct separation between physical boundaries, and structures characterized by explicitly defined domains are achieved. The Finite Element Method (FEM) is utilized to solve the soil and structure domains, incorporating the Perfectly Matched Layer (PML) strategy used for absorbing dynamic waves and simulating an infinite domain. The optimization problem is addressed by using sequential integer linear programming via the TOBS-GT (Topology Optimization of Binary Structures with Geometry Trimming) method. The objective is to obtain optimized structural foundation layouts considering a prescribed concrete volume fraction. The sensitivities of the problem are computed via semi-automatic differentiation. The numerical results present the effectiveness of the proposed methodology in designing 3D structural foundations and the potential for real-world applications in tower-like structures, e.g., onshore wind turbines.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE PRECIPITATION DEGREE: A NEW HYDRATION VARIABLE DESCRIBING UNIVERSAL HYDRATION PROPERTIES OF WHITE CEMENT PASTES

Nabor Jiménez Segura[1]*, Bernhard Pichler**[2] *and Christian Hellmich*[2]

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[2]*Vienna University of Technology*

ABSTRACT

Hydration models have long relied on the hydration degree as the standard variable, but innovative evaluation of proton nuclear magnetic resonance relaxometry results of hydrating white cement pastes has led to the introduction of a new hydration variable which is likely to revolutionize our understanding of cement hydration, see [1]. Unlike the hydration degree, which is focused on the residual amount of cement clinker, the new precipitation degree refers to the distribution of hydrogen in the microstructure of cement paste. The precipitation degree is equal to the amount of hydrogen bound in solids divided by the total amount of hydrogen in the material. This newly introduced variable describes the evolution of hydrogen in gel pores, capillary pores, solid C-S-H, and portlandite in a way that can be shown to be independent of the initial water-to-cement mass ratio, the curing temperature, and the storage conditions: either sealed or underwater storage. As for the reaction kinetics, the rate of the precipitation degree is governed by one specific value of the activation energy and a linear affinity function of the current precipitation degree normalized to its final maximum value. The latter decreases linearly with increasing curing temperature. This can be shown to be related to the decrease in water content of solid C-S-H with increasing curing temperature. Finally, analytical expressions for quantification of the hydration-induced evolution of the volume fractions of gel pores, capillary pores, shrinkage voids, solid C-S-H, portlandite, and cement clinker are derived. They account for the initial water-to-cement mass ratio, the precipitation degree, the temperature-dependent water-to-silica ratio of solid C-S-H, and the storage conditions.

Reference

[1] N. Jiménez Segura, B. Pichler, and C. Hellmich. Mix-, storage-and temperature-invariant precipitation characteristics in white cement paste, expressed through an NMR-based analytical model. Cement and Concrete Research 172: 107237, 2023. https://doi.org/k26n

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE ROLE OF THE HORIZON IN MODELLING FAILURE WITH PERIDYNAMICS

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ABSTRACT

We investigate the effect of the horizon size on failure due to strain and damage localization in the case where peridynamics is a nonlocal theory by its own, which corresponds to most bond-based peridynamics models. Two constitutive relationships are discussed: the micro-elastic brittle model and a progressive damage model. The usual practice with the micro-elastic brittle model is to fit the micro-elastic constant for a given horizon size so that elasticity is recovered. At the same time, the fracture energy provides the critical bond stretch. This methodology yields an indirect determination of the tensile strength of the material, that goes to infinity as the horizon size tends to zero. One cannot fit at the same time the elastic constant, the material strength, and the fracture energy in the micro-elastic-brittle model.

For the damage model, we consider a simple one-dimensional case of failure due to interacting strain waves and investigate the influence of the discretization and the relationship between the horizon and the energy dissipated at failure. The damage model has an additional parameter compared to the micro-elastic brittle model: the softening parameter. It could have been expected that by adding one parameter, the Young's modulus, the material strength, and the fracture energy could be fitted independently from the horizon size. This is not true because the energy dissipation upon fracture remains a linear function of the horizon.

Given the horizon size, the softening parameter could be adjusted to fit the fracture energy. This is exactly the methodology implemented in the classical crack band model, the simplest form of regularization of strain localization due to softening. Surprisingly, such a methodology is very seldom mentioned in the current literature dealing with fracture modelled by peridynamics where the horizon size is considered as a numerical parameter usually.

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A VISCOELASTIC NONLOCAL MODEL FOR DYNAMIC BEHAVIOR OF DIELECTRIC ELASTOMER PLATES

Francesco Paolo Pinnola[1], Alotta Gioacchino[2], Francesco Scudieri[1] and Francesco Marotti de Sciarra[1]*

[1]University of Naples "Federico II"
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ABSTRACT

Some wave energy conversion (WEC) devices are composed by water column (OWC) systems equipped with dielectric elastomer generators (DEGs) at the top. These systems are capable of converting sea wave energy into electrical energy. The structural design of the layered DEG is an important issue, it requires the definition of a proper model to optimize the energetic efficiency of the mechanical system. In this context, the paper presents a dynamical model of axial symmetric elastomeric plate. Its mechanical behavior is studied considering some crucial aspects, i.e., viscoelasticity and nonlocality. Specifically, viscoelastic properties of the elastomer are considered by fractional rheological model and nonlocality is modeled by recent stress-driven approach. In this way, the stress-strain relation is described by a time-dependent nonlocal constitutive law. The resulting dynamical problem is solved by means of a modal decomposition procedure, evaluating the steady-state response and providing results in terms of power spectra. Presented results show how geometry, nonlocal parameter and viscoelastic coefficients influence the mechanical response and the main frequencies of the structure. Numerical and theoretical outcomes can help in the design of these energy-harvesting devices.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN INNOVATIVE ONLY-OUTPUT METHOD USEFUL FOR HISTORIC MONUMENTS

Salvatore Russotto[1], Chiara Masnata[1] and Antonina Pirrotta[1]*

[1]Engineering Department

ABSTRACT

Abstract. Structural Health Monitoring (SHM) is nowadays common in many branches of engineering since it allows to have a continuous or periodic report of the structural conditions and therefore to intervene promptly if there are incipient damages. The first step to perform a SHM is the identification of the dynamic parameters, i.e. natural frequencies, damping ratios and modal shapes, and it is a crucial step since a modification of the structural parameters can be a direct consequence of structural damages. Among the structural identification methods, Operational Modal Analysis (OMA) methods have received increasing attention from the researchers since they do not require the knowledge of the structural excitation that is due to ambient vibrations and that is usually modeled as a white noise. This aspect makes this kind of methods cheaper and simpler than the classical Experimental Modal Analysis (EMA) methods. In this paper an innovative OMA method is proposed. It is a semi – automated method that allows to identify natural frequencies, damping ratios and modal shapes of a structural system and that can be used also from users that have not knowledge in stochastic dynamics and signal analysis. Specifically, first of all the modal shapes are estimated through the use of signal filtering techniques applied on the stochastic properties of the output process and then natural frequencies and damping ratios can be estimated from the mono – component analytical signals obtained by performing a decomposition of the analytical signals matrix. The proposed method has been used to perform the dynamic identification of a real historic building situated in Palermo, i.e. Chiaramonte palace, and the results obtained have been compared with those obtained by using other OMA methods.

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Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SHAPE MORPHING WITH SWELLING HYDROGELS AND EXPANDING FOAMS

Abigail Plummer[1], Caroline Adkins[2], Tom Marzin[3], Julien Le Dreff[3], Sujit Datta[3], P.-T. Brun[3] and Andrej Košmrlj[3]*

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ABSTRACT

Materials that increase in size offer intriguing possibilities for shape morphing applications. Here, we explore two such systems---swelling polyacrylamide hydrogels and expanding polyurethane foams. The hydrogels swell by absorbing water into crosslinked polymer networks. They can therefore be modeled by coupling solvent migration with the deformations of a hyperelastic solid. In contrast, the foams initially behave as liquids with viscosity and volume increasing in time, responding as an elastic solid only when close to solidification. We investigate how these expanding materials can be sculpted by complex environments with obstacles and trenches and discuss the relevance of our findings for industrial and manufacturing applications.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PRE-TRAINED TRANSFORMER MODEL AS A SURROGATE IN MULTISCALE COMPUTATIONAL HOMOGENIZATION FRAMEWORK FOR ELASTOPLASTIC COMPOSITES

Zhongbo Yuan[1] *and Leong Hien Poh**[2]

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ABSTRACT

A composite material typically exhibits complex behavior at the engineer scale, arising from the interactions between its underlying constituent phases, as well as the competitions between micro-processes. It is generally a daunting task to develop an engineering model to adequately capture the essential micro mechanisms that propagate onto the macro scale. To this end, the multiscale computational homogenization method enables a consistent coupling across length scales, to give results that compare well with direct numerical simulations (DNS) having the full micro-structural details, without the need for any constitutive assumptions nor calibrations at the macro scale. Despite its predictive capabilities, the typical computational homogenization method is still computationally too expensive for most practical problems, as the coupling between micro and macro scales are solved simultaneously during its numerical implementation. In this presentation, focusing on the elastoplastic behavior of fiber-reinforced composite, we address this bottleneck with an offline development of a microscopic surrogate model for a given micro-structure, to be incorporated into a standard nonlinear FE framework, for rapid online implementations at the macro scale. For the offline training phase, we adopt the transformer-based architecture within a pre-training and fine-tuning framework. The proposed pre-trained transformer model is capable of parallelizing computations to effectively capture global dependencies within the strain-stress data sequences. To reduce the data generation cost, a constructed source representative volume element (RVE) having a single central heterogeneity with an identical volume fraction with the target RVE is utilized, to rapidly generate a huge source dataset for a pre-training process. The surrogate model is incorporated into a macro FE framework, and its predictive capabilities illustrated via the generic loading of two specimens with different microstructures, each having a different loading-unloading path.

APPLICATION OF MULTISCALE MATERIAL MODELING IN STRUCTURAL TOPOLOGY OPTIMIZATION

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ABSTRACT

Topology Optimization (TO) is a conceptual computational design tool which aims to find the optimal material distribution within a given design space for a desired structural performance. The process essentially entails minimizing an objective function while satisfying certain constraints. From a structural performance point of view, TO processes are typically categorized in two distinct groups: “volume-constrained compliance minimization” and “stress-constrained volume minimization”. In the former, the goal is to minimize the deformation of the structure with a given volume; while in the latter, the goal is to minimize the structure’s volume while constraining the stresses to remain within certain limits. Most commonly, TO algorithms rely on Finite Element Method (FEM) simulation of the structure for discretizing the structure and calculating the objective and constraint functions.

Traditionally, the structural analysis in both of the aforementioned TO strategies are based on macroscopic linear elastic behavior of the material. However, many important structural materials possess microstructural features that are inevitably neglected by macroscopic models. Further, TO-based designs are better suited for novel manufacturing and construction techniques, such as 3D printing of concrete, which, in turn, introduce additional microstructural features to the material. In this research, we utilize a multiscale material model to enhance the TO schemes by studying the material as a collection of grains interacting with their neighbors through different inter-granular mechanisms. At each material point within the FEM analysis, the material behavior is derived by integrating the behavior of grain-interactions in all directions, enabling us to capture the effects of the anisotropic evolution of microstructure during loading, material nonlinearity, as well as the asymmetric material behavior under tension and compression. By implementing this micromechanics-based material model into the TO algorithm, we are able to predict the optimized topology of the structure with correct considerations from the grain-scale behavior. Our results include optimized topology of concrete structures, demonstrating the ability of this microstructure-informed algorithm to take into account the material’s asymmetric behavior under tension and compression.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRONG FORM MESHLESS GRADIENT NONLOCAL DAMAGE FORMULATION VIA HIGH ORDER CONSTRAINED POLYNOMIAL DIFFERENTIAL OPERATORS

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ABSTRACT

Strong form meshless analysis methods are nowadays receiving a renewed attention because they can offer higher accuracy, and lower computational cost, as they avoid background cell integration associated with solving the weak form. Recent work by the authors has focused on formulating and implementing a meshless solution strategy for the strong form of elastic (and plastic) solids on the basis of a novel class of partially constrained polynomial finite-difference (FD) differential operators over arbitrary nodal grids that bypass ill-conditioning (and singularities) guaranteeing robustness and high accuracy. This study extends this meshless analysis formulation to solids with nonlocal brittle damage. Unlike local damage continua, which assume the damage to depend on the history of stresses/strains at a point, nonlocal damage continua recognize that the evolution of damage at a point is influenced by the history of stresses/strains over its vicinity, which is determined by a length scale factor. In the proposed constitutive relations, the damage factor is selected to be the nonlocal variable and, thus, it has a local and a nonlocal counterpart. Compared to local continua, this approach introduces an additional set of field equations, the gradient nonlocality relations (between local and nonlocal damage factors) together with their respective homogeneous Neumann boundary conditions. Because these gradient equations include 2nd order spatial derivatives of the nonlocal variables, this study first extends the aforementioned class of partially constrained polynomial FD differential operators to produce higher order derivatives by integrating higher order polynomials together with the concept of short-range interpolation and long-range approximation used for the low order FD operators.

In formulating a meshless solution method, the continuum is first discretized into a set of arbitrary nodes, and FD differential operators are generated for this set of nodes. Subsequently, these FD operators are used to convert all field differential equations, namely equilibrium, strain-displacement equations, and gradient nonlocality equations, into algebraic equations over a spatially discretized solid domain. The resulting equations are then modified to include natural BCs (for equilibrium equations) and homogeneous Neumann BCs (for nonlocality relations). Essential BCs are applied at the nodes as in typical FEM. Examples will be presented for 2D problems. Results provide insights into the capabilities of this approach to tackle nonlocal damage problems.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ML-REGULARIZED FUNCTIONALS FOR IMAGING IN COMPLEX ENVIRONMENTS

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ABSTRACT

Motivated by the recent advances in deep learning that gave rise to a suit of powerful tools for signal denoising, data transformation/compression, and image processing, this work aims to develop an automated framework for ultrasonic imaging by way of the sampling-based indicators and their derivatives for imaging in complex (or unknown) backgrounds. The overarching objectives are two-fold: (1) establishing a systematic approach to autotune the hyperparameters of data inversion, and (2) integrating the imaging process and adaptive neural architectures for preconditioning of “raw” experimental data and post processing of indicator maps to enable compressive sensing.

Given the highly ill-posed nature of remote sensing problems, regularization parameters in the cost functions are key to high-quality data inversion. The multi-fidelity nature of measurements in many applications along with the presence of high levels of noise in extreme environments, such as in monitoring of AM builds during fabrication, has made the process of gauging such parameters somewhat ad hoc and computationally expensive. In this talk, we demonstrate the possibility of learning the regularization parameters effectively and efficiently by neural maps. It is further highlighted that in the case of laser ultrasonic experiments, the identified parameters are quite insightful in noise characterization which (a) informs the pre-conditioning process, and (b) enhances the reconstruction results.

For completeness, a comparative analysis of convectional methods and the proposed approach in waveform inversion is provided using synthetic and experimental data.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCOVERING THE HIDDEN EMISSION OF ROADWAY NETWORK

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ABSTRACT

Road transportation, historically recognized as a significant contributor to greenhouse gas emissions, currently faces scrutiny in the context of today's ever-increasing travel and mobility demands. This necessitates the meticulous identification and subsequent mitigation of transportation-related emission sources. Among these sources, pavement-vehicle interactions (PVIs), which are often underestimated in their impact, play a tangible role in emissions. In this study, a mechanistic approach is adopted to uncover the scaling relations for these hidden PVI-induced energy dissipation sources that could potentially increase fuel consumption by as much as 15%. Exploiting the highly scalable nature of the approach, we conduct an analysis of the major roadway network for a few states in United States and provide insights into the statistical distribution of excess fuel consumption and the related environmental impacts at different length scales, ranging from individual road segments to the entire roadway network.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INFLUENCE OF SINUSOIDAL FILAMENT GEOMETRY ON INTERFACE INTERLAYER BOND STRENGTH OF 3D PRINTED CONCRETE

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ABSTRACT

The construction industry has great potential for growth in terms of sustainability and efficiency. In recent years, there have been signs that the industry is progressing towards digitalization. Adopting new technology and automated processes opens the gate for further digitalization and automation within the construction industry. In this regard, the civil engineering industry has recently paid more attention to 3D-printed concrete due to reduced construction and labor costs, production time, and construction waste. These decrease the concrete's carbon footprint and increase concrete sustainability (Liu et al 2023). 3D-printed concrete is extruded through a nozzle, depositing linear filaments in successive layers to construct objects. The printed body often suffers from instability failure due to insufficient stiffness when the structure bears the dead weight and the mass of the upper layers in concrete 3D printing. In addition, an inevitable cold joint is formed at the contact surface of extruded layers. One of the critical factors affecting the interfacial bonding properties is the geometry of the filament. In this study, the enhancement of interlayer bond strength is studied by altering the geometry of the printed filament. Brazilian disks were used to study the failure performance of sinusoidal geometries with three different amplitudes and three frequencies on the interlayer bond strength of printable concrete compared to a flat interface. Finally, we analyzed the strains and stresses in each sample using the finite element method and digital image correlation. This approach helps predict and understand the fracture paths in the samples and, consequently, design a robust 3D printed structure.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING MECHANICAL PROPERTIES OF CEMENTITIOUS MATERIALS THROUGH AUXETIC MATERIALS

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ABSTRACT

Innovations in construction materials are pivotal for the development of more durable and resilient structures. This study introduces auxetic structures as a novel reinforcement method in cementitious composites. Auxetic materials are characterized by their negative Poisson's ratio, a unique property where the material exhibits compressive strength in multiple directions upon being compressed. We explored the efficacy of three distinct materials for the auxetic structures: Polylactic Acid (PLA), Aluminum, and Stainless Steel 316i.

To assess the performance of these auxetic reinforcements in cement, we employed finite element simulations coupled with digital image correlation techniques. This approach allowed us to analyze the stress and strain distribution within the cement structure under various load conditions. Each material (PLA, Aluminum, and Stainless Steel 316i) was evaluated for its ability to improve the overall mechanical properties of the cement matrix compared to control samples and ultra-high-strength cement.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NON-STATIONARY STOCHASTIC DYNAMIC LOADS IN TOPOLOGY OPTIMIZATION OF STRUCTURES

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ABSTRACT

Topology optimization has been extensively explored in the context of static determinist scenarios; however, the structural engineering field is predominantly characterized by dynamic stochastic loads, often non-stationary in nature (for example earthquake loading). This study introduces a novel methodology for directly addressing stochastic non-stationary topology optimization, offering an important alternative to traditional deterministic approaches and current stochastic models. The proposed methodology is applied in the optimization of two buildings, with 9- and 20-stories high, respectively. The paper first addresses the challenges posed by stochastic non-stationary loads and then provides a comparative analysis between optimized designs using both stationary and non-stationary frameworks. The findings of this study provide valuable insights into the applicability of stationary topology optimization, demonstrating its efficacy in a diverse range of non-stationary scenarios, particularly related with earthquake engineering. The reduced computational time associated with stationary optimization is highlighted as a critical advantage, promising substantial time savings while using topology optimization for building design. The implications of these findings extend beyond theoretical advancements, presenting tangible cases where the use of stationary stochastic loads is adequate to obtain optimal designs for non-stationary problems.

A HYBRID MACHINE LEARNING AND IMAGE PROCESSING APPROACH FOR SCALE INVARIANT CRACK WIDTH QUANTIFICATION

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ABSTRACT

This work presents a significant advancement in the field of automated infrastructure monitoring, introducing a refined algorithm capable of detecting and quantifying concrete cracks with a high level of precision. The algorithm is tailored to quantify cracks with widths as small as 0.2mm with less than a 15% margin of error, directly addressing the need for accurate field evaluation of concrete deck performance.

The key innovation in this development is the algorithm's scale invariance, a crucial aspect that addresses a notable gap in existing literature. Traditional methods often require images of fixed sizes and specific angles, losing effectiveness when crack sizes fall outside a certain range. This scale invariance enables consistent and accurate quantification across a spectrum of crack sizes and varying image capture distances, overcoming a common limitation in transitioning lab-trained algorithms to diverse field scenarios.

The algorithm combines machine learning crack segmentation techniques, adept at identifying potential cracks, with edge detection algorithms for precise crack boundary delineation. By fusing crack segmentation and edges through a union operation and refining the results, it produces crack masks with pixel widths representative of actual crack sizes. This approach has been proven effective across various scales, even in submillimeter crack width measurement, significantly enhancing the crack detection and quantification process over standard computer vision methods.

Extensive validation was carried out by comparing the algorithm's output with manual measurements of cracks in a series of high-resolution images, demonstrating its efficacy. The study explores the potential of this method to improve automated crack mapping in Department of Transportation (DOT) applications.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INSTABILITIES IN GRANULAR MATERIALS IN FLEXIBLE BOUNDARY PLANE STRAIN CONDITIONS

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ABSTRACT

Instabilities in granular materials are marked by the development of heterogeneous deformations in “single-element” experiments. However, once the instability is onset, it becomes a boundary value problem. The present study uses a flexible boundary plane-strain (FB-PS) apparatus (Bhattacharya and Prashant 2020) to characterize the instability behaviour under undrained conditions. It permits pressure control along both the lateral (σ3) and principal (σ1) loading directions. The flexible boundaries fabricated using butyl rubber material allows uniform pressure application (both σ3 and σ1) as compared to rigid boundaries (Rowe and Barden 1964; Arthur 1988), which is a distinct advantage over previously developed plane-strain test setups. Consolidated undrained tests are performed with two different boundary conditions, i.e., flexible and mixed boundaries, to study the influence of boundary rigidity at two relative densities (15% and 50%) and two confining pressures (σ3'=25 kPa and 50 kPa). Flexible boundary signifies employing butyl rubber flexible membranes along all sides. While in mixed boundary conditions, additional rigidity is provided along the principal loading direction (σ1) using thin aluminium sheets of thickness 0.3 mm with the flexible butyl rubber membranes. The soil specimen could resist greater devaitoric stress in the flexible boundary case. Moreover, the excess pore water pressure response is more contractive with flexible boundary as compared to mixed boundary. Instability response is studied using both global and local deformation measurements using image analysis techniques. The development of non-homogeneous deformations is comapritvely slower in the case of flexible boundary as compared to mixed boundary case.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ECOCFTRACK: ADVANCED DIAGNOSTIC, MONITORING, AND TRACKING DEVICE FOR AFFORDABLE CYSTIC FIBROSIS CARE

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ABSTRACT

Cystic fibrosis (CF) is a genetic disorder that primarily affects the respiratory, digestive, and reproductive systems. Approximately 40,000 children and adults in the United States suffer from cystic fibrosis and about 1,000 new cases of cystic fibrosis are diagnosed each year in the U.S. Despite the existing methods available for diagnosing and monitoring cystic fibrosis patients, a rapid, efficient and cost-effective system is needed to diagnose and monitor the treatment process cystic fibrosis. Since sweat test is considered the most reliable for diagnosing and monitoring for cystic fibrosis, wearable sweat biosensors have gained huge traction due to their potential for non-invasive health monitoring. As high energy consumption is a crucial challenge in this field, efficient energy harvesting technology like the Triboelectric Nanogenerator (TENG) from human motion represents an attractive approach to sustainably power wearable sensors. Despite intensive research activities, most wearable energy harvesters suffer from complex fabrication procedures, poor flexibility and being inconvenient, making them unsuitable for continuous biosensing. Here, we propose a flexible, mass-producible, and effective TENG based wearable sensor for diagnosing and monitoring cystic fibrosis patients that effectively extracts power from body motion through flexible sensors. With the sweat test and fitness workouts being the most common methods for diagnosing and treating cystic fibrosis patients respectively, this sensor uses the ion concentration in sweat to diagnose cystic fibrosis patients and uses the varying sweat concentration of the patient for activity tracking.

USE OF VALUE OF INFORMATION ANALYSES FOR DECISION-SUPPORT OF SCOURED BRIDGES: CASE STUDY

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ABSTRACT

Bridge infrastructure in Europe and the US is aging and becoming more vulnerable to damage. With a changing climate, issues such as flooding are becoming more frequent, placing a high burden on already stressed bridges. Scour erosion is a major issue for bridges and relates to the removal of soil from around foundations by flowing water, and is significantly exacerbated during flooding. Scour is the leading cause of bridge failure worldwide. Infrastructure asset managers are beginning to focus efforts on moving away from visual-based inspections towards implementing smart monitoring solutions. There now exists a wealth of structural health monitoring approaches that claim to assist with damage evaluation of structures. Many of these rely on measuring response properties of a bridge, such as changes in dynamic behaviour, and inferring the presence of damage from these responses. Asset managers must decide on the financial viability of installing such systems on bridges on a network, a decision often governed by financial constraints, given the usually high number of individual bridges that may require attention. In this work, recent research into using Value of Information analyses to assist asset owners with deciding on the financial viability of implementing health monitoring approaches for the purpose of scour evaluation is discussed. A case study is described surrounding the installation of a frequency-based health monitoring strategy on a target bridge. Multiple flood events and different scenarios are considered.

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

APPLICATIONS AND IMPLEMENTATION OF 3D SCANNING FOR DAMAGE EVALUATION AND CAPACITY ESTIMATION OF CORRODED BRIDGE BEAM ENDS

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ABSTRACT

With aging infrastructure nationwide, a major challenge facing bridge engineers and inspectors is the evaluation of these structures. In the case of steel structures, corrosion is the major cause of damage, particularly at the end of the beam at the bearing leading to a reduction in capacity and stability related buckling failures. The research team at the University of Massachusetts acquired several naturally corroded beams from across the New England states for documentation and load testing. The research focused on developing a protocol for documenting section loss via LiDAR and 3D scanning technologies using in house developed codes. In addition, the research team tested the specimens until failure was observed and compared these results to the current predictions by each New England State.

For other untested beam specimens, a study was conducted between scans of unclean and clean corroded ends to analyze delamination and section loss trends. Cleaning the beam end from paint, pack rust, and other debris is an unavoidable roadblock that bridge inspectors have to face in order to perform accurate measurements of section loss. To understand this phenomena further, scans were conducted pre and post cleaning the end. The resulting thickness maps were created and the desired parameters such as average thickness and statistical outputs were analyzed thoroughly. This ongoing work has a goal of estimating section loss using uncleaned beam end data and the exploration of implementing AI.

The current state of practice for estimating section loss on corroded steel ends is very limited both in quality and quantity of measurements. Ultimately, the more accurate section loss measurements via scanning and to provide greater accuracy in the capacity estimation of corroded ends. The results of this work have the potential to assist bridge engineers in making educated decisions in load rating and repair with higher confidence and vast data.

DEEP LEARNING BASED INITIAL DEFORMATION MODELING IN SHIELD TUNNEL: PRELIMINARY RESULTS

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ABSTRACT

By the end of 2022, mainland China has 8,008 kilometers of shield tunnel subway lines in operation. Currently, in tunnel design, construction, and operation, a widely accepted assumption posits that tunnels are initially constructed in an intact state. However, anomalies have been observed wherein tunnels exhibit large convergence (deformation) with small cracking (internal force). Such anomalies suggest the presence of initial deformation, caused by temporary loads during the construction phase.

To the best of our knowledge, initial deformation has not been fully studied in the field of shield tunnel engineering, but it is a crucial factor in the whole life cycle management of shield tunnel. Initial deformation typically comprises force-induced deformation and rigid body deformation. The former, force-induced deformation, is essentially a complex load history problem, requiring nonlinear analysis of material property. The latter, rigid body deformation, deteriorates the mechanical behavior of longitudinal joints, demanding refined modeling of tunnel structures. Consequently, the modeling of tunnel initial deformation often resorts to large-scale complex numerical simulations, which are time-consuming and difficult to update with measured data.

To facilitate the effective modeling for tunnel initial deformation and overcome the heavy computational burden, a deep learning based multi-fidelity network is constructed to predict convergence, cracking, concrete crushing, and joint opening (structural responses) based on initial deformation, external loads, and material properties (structural parameters). This model incorporates a low-fidelity network trained on synthetic data generated by finite element method (FEM) models and a residual network trained on real data collected from experiments and field monitoring. The synthetic data are abundant but have biases due to simplifications and assumptions of the FEM model. Conversely, the real data are limited but have relatively small biases. The synthetic data enforce the network with physical law, while the real data mitigate biases from synthetic data. The proposed multi-fidelity network design presents a viable approach for the fusion of both types of data. Preliminary results demonstrate that the proposed method achieves a balance between efficiency and accuracy.

Data-driven methods and research for physical testing in structural engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNIFIED SHEAR CAPACITY EQUATION FOR REINFORCED CONCRETE MEMBERS BASED ON A VARIABLE-ANGLE TRUSS MODEL AND MACHINE-LEARNING-CALIBRATED COEFFICIENTS

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ABSTRACT

Historically, the development of shear capacity equations for reinforced concrete (RC) beams and columns has originated from the conceptualization of a resisting mechanism. Recently, the use of data-driven approaches based on standard regression techniques has evolved by exploiting machine learning techniques. In contrast, this research advances a hybrid approach to formulate shear capacity equations for RC beams and columns with rectangular/square cross-sections. This method enhances a mechanics-based, code-conforming formulation through the integration of a machine-learning-aided approach. Specifically, the Genetic Programming technique is employed to enrich the shear capacity equation based on a variable-angle truss resisting mechanism. This integration results in the formulation of novel expressions for the two key coefficients governing the concrete contribution from available experimental data. The performance of the newly derived equation is initially assessed for beams and columns with solid cross-sections under uniaxial shear. Subsequently, the analysis extends to columns with hollow cross-sections subjected to uniaxial shear. The study concludes by outlining the ongoing experimental and theoretical efforts to extend the proposed model to biaxial shear. Hence, this research establishes a unified shear capacity equation for RC beams and columns. Additionally, it demonstrates the advantages of merging mechanics-based and data-driven methods. This integration proves beneficial in developing capacity equations, as it preserves the physical meaning as well as the general validity of a well-established resisting mechanism while enhancing the accuracy through a machine learning technique.

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Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTELLIGENT AUTOMATIC OPERATIONAL MODAL ANALYSIS

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ABSTRACT

This work presents a novel approach for automatically identifying the modal characteristics of linear structures from their response to ambient vibrations. The proposed methodology is named Intelligent Automatic Operational Modal Analysis (i-AOMA) and comprises two main phases. In the initial phase, the Covariance-based Stochastic Subspace (SSI-cov) algorithm is executed with quasi-random samples of its control parameters, namely the number of block rows, the length of the data time windows, and the model order. Afterward, the resulting stabilization diagrams undergo a statistical processing through Kernel Density Estimation to prepare a training database for the intelligent core of i-AOMA. This core, employing a machine learning technique (specifically, a Random Forest algorithm), predicts optimal combinations of control parameters of the SSI-cov algorithm. The second phase of i-AOMA involves iteratively generating quasi-random control parameter samples. If a sample is deemed feasible by the intelligent core of i-AOMA, then the SSI-cov algorithm is applied; otherwise, a new sample is considered. This iterative process continues until a statistical convergence criterion is met. Consequently, final modal estimates are derived from the stabilization diagrams, and relevant statistics are computed to quantify the impact of epistemic uncertainties attributable to the variability of the control parameters. The complete Python source code for i-AOMA is publicly accessible through web repositories. Experimental applications to large structures will be presented in order to demonstrate the validity of the proposed methodology.

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MULTI-DIMENSIONAL RELIABILITY ASSESSMENT AND RESILIENCE-BASED ANALYSIS OF ELECTRIC POWER NETWORKS

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ABSTRACT

Power distribution systems are the most vulnerable part of electric power networks (EPNs) to natural hazards and environmental events such as hurricanes, earthquakes, and floods. Wooden electricity poles and their connected spanning wires stand exposed to direct wind forces, falling debris, and the destructive power of nature, causing power outages for extended periods and incurring both direct and indirect losses. This research proposes a comprehensive framework for enhancing the resilience of EPNs through adaptive risk assessment, resulting in predictions and proactive management decisions that can promote the reliability of power delivery systems.

The capacity of wooden poles is influenced by their class, geometry, age, and the surrounding environmental conditions that expedite their deterioration. On the other hand, the different combinations of wind speed and its fluctuation and direction form a wide variety of loading scenarios. Hence, a holistic multi-dimensional reliability assessment employing class fragility development and analysis to address these complications is presented by capturing and analyzing the response poles to different wind scenarios. The comprehensive resilience-based approach employs advanced modeling techniques, statistical analysis, and machine learning to develop the multi-dimensional fragility functions. Allowing for numerous factors on both the demand and capacity sides and their inherent uncertainties to be considered, in addition to the inclusion of various modes of failure and their joint probabilities. Large sets of random variables mimicking wind probabilities based on historical data have been generated and paired with sets of random variables related to the properties of the poles and their wires, producing sizable realizations for capacity and demands scenarios, where each realization is structurally analyzed and used to build the cumulative failure probability graphs, i.e., fragility functions.

The presented framework has been scaled and applied to a case study region in the US, resulting in a comprehensive view of the current resiliency of that grid and expanded for proactive resilient-based decisions to be made in response to the intricacies of weather events and environmental conditions, ultimately promoting the development of resilient energy infrastructures.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN EXPERIMENTAL STUDY FOR ESTIMATION OF RESIDUAL STRENGTH IN CONCRETE BEAMS UNDER FATIGUE LOADING

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ABSTRACT

Concrete structures such as bridges, and offshore platforms are subjected to time-varying oscillatory loads, which causes damage and stiffness degradation due to fatigue. The estimation of residual strength, when subjected to fatigue damage is an important problem in the design and maintenance of concrete structures. A lot of experimental research [1,2] is devoted in determining the fatigue life of concrete elements. However, not many studies have been carried out to determine the residual strength of concrete structural elements when affected by fatigue damage.

In this work, an experimental study is undertaken to estimate the residual strength of concrete beams that are damaged from constant amplitude fatigue loading. Concrete beams of three different sizes are subjected to pre-determined constant amplitude fatigue load cycles. This is followed by a monotonic static loading to determine its residual strength. The response of the beams is measured through acoustic emission (AE) sensors, digital imaging, and crack opening displacement gage. The AE parameters such as events and cumulative energy are analysed to obtain a quantitative measure and study the mechanisms of microcrack evolution. Compliance measurements are taken through loading and unloading cycles during the post-peak softening response of damaged beams and compared with undamaged specimens.

It is seen that the stiffness and strength decrease at a slow rate when the beams are subjected to fatigue loading up to about 80% of its life beyond which the decrease is significant. This indicates that the rate of evolution in damage due to microcracking upon fatigue loading is a slow process and increases significantly close to the final failure.

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https://doi.org/10.1016/j.mechmat.2020.103490

Mechanics of soft synthetic and biological materials: Theory, simulation, and experiment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRENGTH OF A NOVEL CYCLIC PEPTIDE UNDER AQUEOUS AND AIR ENVIRONMENTS

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ABSTRACT

Biomaterials have increasingly become a source of inspiration for developing materials exhibiting strength and toughness. Embracing this bioinspiration concept, a novel class of nanomaterials based on the side-chain-to-side-chain polymerization of cyclic β-peptide rings has been introduced, demonstrating mechanical properties surpassing those of natural silks. This study delves into the mechanics of this polymerization process through comprehensive molecular dynamics simulations.

Utilizing unbiased steered molecular dynamics, we analyze the strength differences between polymerized and unpolymerized cyclic β-peptide rings in both aqueous and vacuum environments. This approach allows for a detailed investigation of the impact of environmental conditions on the mechanical behavior of these cyclic peptides. Our findings show a stark contrast in material properties: unpolymerized peptides exhibit brittle characteristics. In contrast, polymerized ones demonstrate resilience, withstanding significant stress post-initial failure and exhibiting large strain-to-failure values. Intriguingly, the strength of the cyclic peptides is notably higher in water than in a vacuum.

Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENGINEERED BIOLOGICAL CONSTRUCTION MATERIAL: SELF-HEALING CARBON NEGATIVE ENZYMATIC CONSTRUCTION MATERIALS (ECM)

Shuai Wang[12], Nima Rahbar[1] and Suzanne Scarlata[1]*

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ABSTRACT

Concrete, a mixture of calcium silicate hydrates (CSH) has become ubiquitous as a building material, used extensively in infrastructure such as bridges, airport runways, and buildings. However, these materials are also significant contributors to anthropogenic carbon dioxide (CO2) emissions. As a result, there is a growing need to develop sustainable alternatives that minimize the carbon footprint of cementitious materials. Although, strategies such as point-source CO2 capture, renewable fuels, alternative cement, and supplementary cementitious materials can yield substantial reductions in cement-related CO2 emissions, emerging enzymatic technologies based on enzymatic biomineralization mechanisms have the potential to revolutionize the production of concrete and significantly reduce its carbon footprint. In this presentation, inspired by the extremely efficient process of CO2 transport in mammal cells, a self-activated healing mechanism for a cementitious matrix and an ultra-strength self-healing enzymatic construction material (ECM) are proposed using Carbonic Anhydrase (CA) enzyme. The critical findings from ECM can be highlighted that the compressive strength of ECM is more than two times of minimum acceptable cement mortar and significantly higher than any currently available biological construction materials. The specific strength of ECM is similar to lightweight concrete. In terms of self-healing, ECM can endure six healing cycles, with damage at the central flaw of the medium-scale beam, with a loss of about 50% of overall strength. Noted that the self-healing process only consumes carbon dioxide without an additional source of energy. A crystal growth model of ECM is governed by diffusion and developed for mineral bridge dimension prediction analysis. We also describe a method that allows rapid curing under ambient conditions. We show that a low-power laser (3W at 808 nm) can cure ECM to an optimal mechanical strength in 12 h, which can be compared to the 14-day period needed for in situ air drying. In addition, the incorporation of nanoparticles allows rapid self-healing of large-scale flaws. This method establishes an on-site manufacturing capability for ECM and other construction materials and supports thermal controllability of the local structure in low-temperature regions.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMIC CRACK PROPAGATION IN FUNCTIONALLY GRADED MATERIALS UNDER THERMAL SHOCK: A NOVEL PHASE FIELD APPROACH

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ABSTRACT

Functionally graded materials (FGMs) have emerged as a groundbreaking class of composites, offering tailored properties for diverse applications. While extensive research has focused on the mechanical aspects of FGMs, there is a critical need to comprehend crack initiation and propagation under intense thermal loads. This presentation introduces an innovative computational framework designed for the dynamic simulation of crack propagation in FGMs subjected to thermal shocks.

Our methodology integrates a coupled thermal-mechanical phase field model of brittle fracture, featuring a temperature-dependent elastic energy density function. The presentation provides a comprehensive overview of the mathematical and implementation aspects of the approach, accompanied by rigorous verification and validation against alternative computational methods and experimental results.

Moreover, our proposed framework is applied to challenging thermal shock scenarios, showcasing its efficacy in capturing the intricate physics governing the coupled thermal-mechanical-fracture behavior of FGMs in extreme environments. The outcomes of this research are pivotal for predicting and averting sudden load-carrying capacity loss and catastrophic failure in applications characterized by severe loading conditions and extreme thermal environments. This work contributes significantly to the advancement of fracture modeling, providing valuable insights for designing resilient materials in demanding operational contexts.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE MECHANICAL BEHAVIOR AND DEVELOPMENT OF STAINLESS-STEEL CELLULAR BONE-SCAFFOLDING VIA ADDITIVE-MANUFACTURING FOR BONE GROWTH AND REPLACEMENT

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ABSTRACT

Critical-sized bone defects represent a significant challenge in the orthopedic field. Limitations on autograft and allograft as treatment techniques led researchers to explore the implantation of artificial bone tissue scaffolds. Bone scaffolds are three-dimensional cellular structures that provide mechanical support and behave like a template for bone tissue formation. The main hypothesis in this research is that the stress shielding phenomenon, known as the bone weakening and reduction in bone density as a result of stiffness mismatch between the bone and the scaffold, is the main cause of bone resorption (loss) that leads to eventual failures of bone implants. The availability of additive manufacturing facilitated the fabrication of bone scaffolds with precise architectural and structural configurations. This study aims to reduce the stress shielding effect by designing and manufacturing a numerically optimized stainless steel bone scaffold with an elastic modulus that matches the structural modulus of the human cortical bone. Diagonal and cubic cell scaffold designs were explored. Strut and cell sizes were numerically optimized with a predetermined pore size to achieve the target structural modulus. The optimized scaffold designs were manufactured using the direct metal laser sintering (DMLS) technique and experimentally tested in compression to validate the finite element analysis (FEA) model and explore the failure mechanisms of both scaffold designs. Scanning electron microscopy (SEM) was performed to characterize the structural configuration of the manufactured scaffolds. Minimal porosity was found in struts and minor variations in strut sizes were observed between the manufactured scaffolds and CAD models. Rough surfaces were noticed due to the metal powder sintering process. FEA results were found to agree with the experimental findings which validate the FEA model. Cubic scaffold exhibited stretch-dominated failure while bending dominated failure accompanied by shearing bands was observed in the diagonal scaffold. The bending and torsional stiffnesses of both scaffold designs have been numerically evaluated and higher bending and torsional moduli were observed in the diagonal scaffold compared with the cubic scaffold. In conclusion, this research presented the ability to optimize, design, and manufacture bone scaffolds using additive manufacturing with mechanical properties that relate to the cortical bone as part of bone tissue engineering, as well as the need to investigate the biomechanical loading behavior and osteointegration properties of the designed scaffolds.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AUTOMATING THE INSTANCE SEGMENTATION OF RC BRIDGES

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ABSTRACT

The application of semantic segmentation techniques aids in delineating specific structural components within the point cloud of bridges. Despite the potential of deep learning, training models for segmenting structural components demands a substantial amount of labeled point cloud data. The acquisition of real bridge point clouds through LiDAR for training deep learning models poses a considerable challenge. To tackle this issue, this study introduces a framework for creating a synthetic point cloud dataset for reinforced concrete Beam & Slab bridges. The study also illustrates the efficacy of deep learning-based approaches for semantic and instance segmentation of bridges using the same dataset. A transformer-based deep learning model, MASK3D, was trained for the instance segmentation of structural components in bridges, with tuning performed on various hyperparameters. The objective is to utilize the trained deep learning model for segmenting point clouds from actual bridges, thereby facilitating the generation of accurate geometric models for real-world bridges.

Key words: Instance segmentation, Bridge, Synthetic point cloud, Deep learning

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A GENERALIZED POLYNOMIAL CHAOS EXPANSION FOR HIGH-DIMENSIONAL DESIGN OPTIMIZATION UNDER DEPENDENT RANDOM VARIABLES

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ABSTRACT

Newly restructured generalized polynomial chaos expansion (GPCE) methods for high-dimensional design optimization in the presence of input random variables with arbitrary, dependent probability distributions are reported. The methods feature a dimensionally decomposed GPCE (DD-GPCE) for statistical moment and reliability analyses associated with a high-dimensional stochastic response; a novel synthesis between the DD-GPCE approximation and score functions for estimating the first-order design sensitivities of the statistical moments and failure probability; and a standard gradient-based optimization algorithm, constructing the single-step DD-GPCE and multi-point single-step DD-GPCE (MPSS-DD-GPCE) methods [1]. In these new design methods, the multivariate orthonormal basis functions are assembled consistent with the chosen degree of interaction between input variables and the polynomial order, thus facilitating to deflate the curse of dimensionality to the extent possible. In addition, when coupled with score functions, the DD-GPCE approximation leads to analytical formulae for calculating the design sensitivities. More importantly, the statistical moments, failure probability, and their design sensitivities are determined concurrently from a single stochastic analysis or simulation. Numerical results affirm that the proposed methods yield accurate and computationally efficient optimal solutions of mathematical problems and design solutions for simple mechanical systems. Finally, the success in conducting stochastic shape optimization of a bogie side frame with forty-one random variables demonstrates the power of the MPSS-DD-GPCE method in solving industrial-scale engineering design problems.

Acknowledgment:
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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SPLINE CHAOS EXPANSION FOR UNCERTAINTY QUANTIFICATION IN LINEAR DYNAMICAL SYSTEMS

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ABSTRACT

This paper leverages recent progress on orthonormal splines for solving uncertainty quantification (UQ) problems from linear structural dynamics. The resulting method, premised on spline chaos expansion (SCE) [1], construes Fourier-like expansion of a dynamic system response of interest with respect to measure-consistent orthonormalized basis splines in input random variables and standard least-squares regression for estimating the expansion coefficients. The SCE proposed is similar to existing polynomial chaos expansion (PCE), but by swapping polynomials for B-splines, SCE achieves a greater flexibility in selecting expansion orders and dealing with subdomains. For this very reason, SCE can effectively tackle stochastic responses that contain locally high fluctuations and that are non-smooth. However, due to the tensor-product structure, SCE, like its polynomial sibling, also suffers from the curse of dimensionality. Numerical results from frequency response analysis of a two-degree-of-freedom dynamic system indicate that a low-order SCE with fewer basis functions eliminates or substantially mitigates the spurious oscillations generated by high-order PCE in calculating the second-moment statistics and probability distributions of frequency response functions [2].

Acknowledgment:
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Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DAMAGE LOCALIZATION OF STRUCTURES USING FULL-FIELD DISPLACEMENT AND DIFFERENTIABLE PHYSICS

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ABSTRACT

Timely localization and quantification of damage are crucial for implementing measures to prevent sudden structural failures. Motivated by advancements in full-field measurement techniques, this study explores the potential of full-field displacement measurements as a non-destructive evaluation tool for large civil structures. We use synthetic data to design various scenarios and identify the potential and limitations of our proposed approach. Our method uses a differentiable physics approach for damage localization and quantification in linear elastic structures with many parameters, as demonstrated in frame and beam models with hundreds to thousands of elements. The differentiable physics model uses the doflin-adjoint framework, and we use gradient-based optimization with regularization to update the relative stiffness of the structure for each element in the mesh. A systematic analysis is performed to evaluate the performance of the proposed methodology. We evaluated our methodology's effectiveness in localizing single and multiple damage, considering variations in damage size and geometry. Furthermore, we examined the model's performance under different initial conditions and assessed the impact of measurement noise and modeling errors, as well as changes in structural geometry, on the overall system's performance. Overall, this study showcases the capability of displacement-based SHM approaches combined with differentiable physics as a future tool for building diagnostics and maintenance.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CORROSION DETECTION OF STEEL-REINFORCED CONCRETE SPECIMENS USING SYNTHETIC APERTURE RADAR

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ABSTRACT

Chloride-induced corrosion attack in reinforced concrete (RC) highway bridges is a common and ongoing issue in New England. If left untreated, steel rebar corrosion can result in cross-sectional loss, internal stress imbalance, and surface cracks in RC components. In this presentation, synthetic aperture radar (SAR) was used for corrosion detection of three RC panel specimens that were subjected to chloride-induced steel rebar corrosion. Three RC panels (30 x 30 x 12.7 cm3) were cast with a No.6 steel rebar (19mm diameter) at their center. One intact RC panel (baseline) and two RC panels corroded by accelerated corrosion test (ACT). Three RC panels were kept in a temperature-controlled environment (73◦∼77◦ F). To detect corrosion, they were scanned by a laboratory 10GHz SAR system with a 1.5GHz bandwidth to develop SAR images. SAR images were analyzed in both time and frequency domains. 1-D and 2-D signal parameters from SAR images were used for corrosion detection and severity classification. Our results indicate that the progression of corrosion is correlated with SAR signal parameters such as maximum and integrated amplitudes.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TWO-PHASE GYROID-LIKE SHELL-BASED ARCHITECTURES WITH IMPROVED ENERGY ABSORPTION CAPACITY

Mehran Rakhshan[1], Alfa Heryudono[1], Lorenzo Valdevit[2] and Mazdak Tootkaboni[1]*

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ABSTRACT

This study presents the design of two-phase metallic cellular structures based on triply periodic minimal surface (TPMS) topologies. Gyroid structures, characterized by TPMS patterns, are synthesized and studied under comprehensive stresses through a combined application of experimental techniques and finite element analysis. The primary focus is the examination of the mechanical behavior manifested when (i) a reparameterization of the gyroid topology is utilized to widen the design space and (ii) some unique additive manufacturing capabilities are deployed that allow for tailoring the material properties of the base metal locally and on demand. The mechanical response, for a limited set of points in the parameter space, is numerically obtained via nonlinear FE models that are validated against experiments. The responses on this limited set of parameter values are then used to build a surrogate model which is subsequently combined with an optimization routine in search for optimal multi-phase architectures.

EXPERIMENTAL TESTS FOR TANK CAR SIDE IMPACT MODEL VALIDATION

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ABSTRACT

The tank car puncture resistance is defined by many variable factors. A controlled testing environment can remove or reduce some of these variables to allow better model validation. However, not all variables can be limited even in the testing environment. Even bigger simplifications and assumptions are associated with the FE model itself. Starting from the geometry and material model to the mathematical solver calculations. It is crucial for the FE model validation to understand the limitations, of the test data and simulation results.

The FRA has a continuing research program to provide the technical basis for rulemaking on enhanced and alternative performance standards for tank cars and review of new and innovative designs that are developed by the U.S. railway industry and by other countries. Under this research program, multiple side impact tests have been conducted to analyze and improve the impact behavior and puncture resistance of railroad tank cars of tank cars used in the transportation of hazardous materials. FE model was developed before each test based on the available information to provide predictions on the tank car performance and establish the impact speed. After the test, the collected data were processed and used to validate the initial FE model.

This presentation will collect experience and lessons learned from over ten tank car side impact tests. The presentation will provide justification for the test setup, type and location of sensors for collecting the data from the FE model validation perspective. Moreover, the data filtration process, use of the data for the FE model validation, and limitations will be discussed.

APPLYING MACHINE LEARNING TO EXPLORE COHESIVE ZONE PARAMETERS IN MIXED-MODE FRACTURES WITHIN COMPOSITE SANDWICH STRUCTURES

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ABSTRACT

In this research, we explore the application of three machine learning algorithms - Support Vector Regression (SVR), Random Forest (RF), and Artificial Neural Network (ANN) - for identifying cohesive zone parameters in the fracture analysis of honeycomb/carbon-epoxy sandwich structures. Conventional experimental methods to determine these parameters often result in multiple, non-unique solutions, and numerical approaches, such as finite element (FE) simulations, pose challenges like the necessity for fine meshes near crack tips. Our study employs a cohesive zone model within FE simulations of the Asymmetric Double Cantilever Beam (ADCB) specimen configuration. The input parameters for our machine learning models include the maximum load, the displacement at maximum load, the area under the load-displacement curve, and the slope of this curve. These inputs form the basis for a comprehensive database of load-displacement responses, serving as the training data for the algorithms. The target outputs of our machine learning models are the cohesive zone parameters, which include the maximum normal contact stress, critical fracture energy for normal separation, maximum equivalent tangential contact stress, and critical fracture energy for tangential slip. Our findings demonstrate that the SVR, RF, and ANN algorithms effectively identify these parameters with remarkable accuracy, both within the range of the training dataset and beyond. This underscores the algorithms' utility in diverse interfacial characteristic scenarios. Further, the performance of these models is enhanced through meticulous hyperparameter tuning and optimization techniques, emphasizing the transformative potential of machine learning in advanced fracture analysis of complex material systems. Moreover, this study includes a detailed comparison of the results obtained from SVR, RF, and ANN algorithms, highlighting their relative strengths and weaknesses in predicting cohesive zone parameters in honeycomb/carbon-epoxy sandwich structures.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GENERALIZED GRANULAR MICROMECHANICS APPROACH TO OBTAIN INJECTIVE MAPPING BETWEEN MATERIAL STATE VARIABLES AND THE STRESS TENSOR

Abhinav Ramkumar[1] and Marcial Gonzalez[1]*

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ABSTRACT

This work presents a generalized Granular Micromechanics Approach (GMA) [1] that allows us to utilize the statistical description of the microstructure (i.e., distributions of contact forces, interparticle distances, and orientation) to parametrize the evolution of the stress tensor for a granular assembly. This work aims to systematically determine the appropriate parametrization of the distribution of microstructural state variables embedded in space and time. The goal of this work is to obtain injective mapping between multivariate distributions of material state variables and the evolution of the stress tensor using internal state variables (ISVs). Internal state variables allow us to capture the important information that leads to the evolution of the system, as is seen in path-dependent and dissipative materials . This analytical model can then be calibrated through experimental observations or particle-scale numerical predictions [2] of the internal state variables identified through this process. We show that we can update the distribution of microstructural state variables and the resulting stress tensor using an affine update for a packing of monodisperse spherical particles. Furthermore, we demonstrate a systematic means of learning the evolution equation for the distribution of microstructural state variables for different loading conditions. This technique can allow one to not only predict the macroscopic evolution of the system, but also inform manufacturing processes to enhance product performance in a wide range of engineering applications.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LATERAL TORSIONAL BUCKLING OF FIXED-FIXED ANISOTROPIC LAMINATED BEAM UNDER MID-SPAN LOAD

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ABSTRACT

In this paper, a generalized semi-analytical approach for lateral-torsional buckling of fixed-fixed anisotropic, thin-walled, rectangular cross-section beams under concentrated load at mid-span/mid-height was developed using the classical laminated plate theory as a basis for the constitutive equations. A closed form buckling expression was derived in terms of the lateral, torsional and coupling stiffness coefficients of the overall composite. These coefficients were obtained through dimensional reduction by static condensation of the general 6x6 constitutive matrix mapped into an effective 2 × 2 coupled weak axis bending-twisting relationship. The resulting two coupled stability differential equations are manipulated to yield a single governing differential equation in terms of the twisting angle. This differential equation with variable coefficients, subjected to fixed-fixed boundary conditions, was solved numerically using infinite series. The resulting solution was found to correlate with the effective lateral-flexure, torsional and coupling stiffness coefficients to yield a general semi-analytical solution. An analytical formula was possible to extract, which was verified against finite element buckling solutions using ABAQUS for a wide range of lamination orientations showing excellent accuracy. The stability of the beam under different geometric and material parameters, like length/height ratio, layer thickness, and ply orientation, was investigated.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYSIS OF A CONCRETE-LINED TUNNEL IN SOIL SUBJECTED TO PROJECTILE EXPLOSION

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ABSTRACT

Recent decades have seen an increased emphasis on the impact of blast loads on structures because of rising threats posed by man-made activities. The propagation of shockwaves in soil and their interaction with the structure is of critical consideration during a blast. The blast-induced shock and its impact on underground and above-ground structures are extremely complicated in the case of a surface or subsurface blast due to the complex nature of the geological medium. A concrete-lined tunnel constructed in a soil stratum is modeled, herein with a burster slab above the tunnel embedded in the surface soil. The complete system is modeled, and its response under the effect of the projectile explosion is determined using the finite element method. The Drucker Prager and the concrete damaged plasticity constitutive models are used to simulate the non-linear behavior of soil and tunnel lining concrete, respectively. We have considered two blast scenarios - i) projectile striking the burster slab leading to penetration followed by an explosion, ii) projectile striking the soil surface directly without the burster slab followed by an explosion. The displacement at varying depths of the soil and along the length of the tunnel is determined. The stress time history at the critical points is analyzed. Reflection and transmission of shock wave phenomena occurring due to the layered soil geometry have been studied along with the attenuation of shock. The presence of the burster slab minimized the damage caused to the tunnel by increasing the attenuation.

Keywords: blast, projectile, attenuation, tunnel, burster slab

QUANTIFICATION OF ELASTIC INCOMPATIBILITIES AT TRIPLE JUNCTIONS VIA A PHYSICS-BASED SURROGATE MODEL

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ABSTRACT

Elevated stresses at grain boundaries resulting from elastic incompatibilities have long been known to drive the premature failure and loss of desirable macroscopic properties in polycrystalline materials. In this work, we create a surrogate model to predict quantitative metrics of incompatibility from grain boundary configurational data. High-fidelity finite element simulations of the plane-strain elastic stress field surrounding cubic-crystal triple junctions subjected to hydrostatic extension were used to generate a synthetic dataset for training the surrogate model. A set of J integrals computed around microcracks placed along the triple junction boundaries were used to quantify the elastic incompatibilities between neighboring grains. The surrogate model, a multi-layer perceptron network, was trained using the grain rotation angles and J integrals as the feature and label data respectively. We demonstrate that the network trained using data produced by the physics-based model establishes an accurate functional dependence between the triple junction angles and the J integrals that enables fast and direct evaluation. We use the surrogate model to efficiently sweep the configuration space and create contour maps of the largest stress intensification at the triple junction as a function of the grain rotation angles. Furthermore, we utilize the analytical properties of the surrogate model to identify the most and least compatible triple junction configurations via optimization. This approach effectively realizes the longstanding objective of a full functional characterization of triple junction incompatibility, as laid out by Tvergaard and Hutchinson (1988).

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Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RUPPEINER GEOMETRY UNVEILING VOLUMETRIC PHASE TRANSITION IN GELS

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ABSTRACT

The field of polymer science has long been interested in the complex interplay between structure, thermodynamics, and mechanical properties in polymeric materials. One of the most intriguing phenomena in this area is volumetric phase transition in gels [1], in which stimulus-sensitive gels, characterized by a three-dimensional network of polymers undergo significant volumetric changes upon exposure to external stimuli such as temperature, pH, composition of the solvent, irradiation by light and electric fields, etc. It is a complex process that significantly impact their mechanical, thermal, and chemical properties. This phenomenon holds immense promise in biomedical and mechanical engineering applications, particularly in scenarios where precise volume control is imperative, such as drug delivery systems, implants, etc.

Despite decades of research, the underlying mechanisms that drive this process still need to be better understood. While phase equilibrium based on Flory-Huggins theory lays a foundational understanding, it falls short in anticipating kinetics and the evolving morphology during the separation process. This study aims at understanding the micromechanical aspects of discontinuous phase transition in polyacrylamide gels using Ruppeiner geometry [2]. Ruppeiner geometry is a specific type of thermodynamic geometry that associates thermodynamic fluctuations of a system with the curvature of the thermodynamic manifold. In this study, metric and curvature are determined using the Landau-Ginzburg type free energy functional involving a squared gradient, in conjunction with the principles of Flory-Huggins theory. The coordinates of the thermodynamic manifold are defined as temperature and the number of solvent molecules. The variations of curvature with temperature and polymer volume fraction are examined, providing insights into microstructural changes and interaction dynamics during phase transition.

The study reveals that Ruppeiner geometry can provide new insights into the underlying physics of volumetric phase transition in polymer materials. Significantly, it proves instrumental in elucidating the intricate connections between microscopic interactions and macroscopic behaviour. The framework equips us with a scalar curvature that is used to understand the microstructure of a gel during phase transition and at critical points. Additionally, it sheds light on the universality class of phase transition, reminiscent of that observed in van der Waals fluids. These findings hold promise not only for advancing our understanding of polymer physics but also for shaping future applications across various disciplines.

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Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A POTENTIAL OF MEAN FORCE-BASED LATTICE ELEMENT METHOD FOR ANALYSIS OF STRUCTURAL SYSTEMS: TOWARDS NONLINEAR AND PROGRESSIVE COLLAPSE ANALYSIS

Shayan Razi[1], Arghavan Louhghalam[2] and Mazdak Tootkaboni[1]*

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ABSTRACT

The pervasive impacts of extreme events and the complex challenges inherent in post-disaster recovery call for the revisiting of engineering approaches to resilience assessment towards the examination of the functional integrity of civil infrastructure. To this end, accurate yet computationally efficient frameworks are needed that allow for the modeling of the failure while accounting for both structural and non-structural components.

In this study, we leverage a Potential-of-Mean-Force (PMF) approach to Lattice Element Method (LEM), a class of discrete methods demonstrated to be advantageous for simulating failure and fracture. The idea is to discretize the system into a set of particles that interact with each other through prescribed potential functions to represent the mechanical properties of different types of structural members. Lending itself to damage assessment due to its discrete nature, the proposed PMF-based LEM transcends the limitations of continuum mechanics approaches and enables the incorporation of a range of effective interaction potentials to simulate the linear and nonlinear behavior of structural components. The calibration procedure for such potentials is conducted via a handshake with continuum mechanics theories, e.g., the Timoshenko beam theory and Kirchhoff-Love plate theory. The process starts with linear elastic behavior and harmonic potentials [1] and is then extended with non-harmonic potentials and section properties that encapsulate the nonlinear responses of the members, e.g., nonlinear moment-curvature relations. Upon the calibration of non-harmonic potentials, ductile failure of the structural members is modeled by breaking bonds between particles according to an energy-based failure criterion. Finally, the utility of the proposed framework is explored through its application in (i) quasi-static nonlinear simulations of large-scale buildings under different loading conditions and (ii) the simulation of progressive structural failure due to the propagation of local structural damage.

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Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL-TIME STATE ESTIMATION OF NONSTATIONARY SYSTEMS USING TOPOLOGICAL DATA ANALYSIS FEATURES

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ABSTRACT

Topological data analysis (TDA) is gaining popularity for classifying complex time series. Its integration with machine learning algorithm architectures shows promise in advancing predictive capabilities for various dynamic systems. Of interest to this paper are high-rate systems, defined as dynamic systems experiencing high-rate (<100 ms) and high-amplitude (acceleration >100gn) events resulting in highly nonlinear and nonstationary dynamics. The use of TDA for the on-time identification of high-rate system states could be beneficial in enabling real-time feedback mitigation and control strategies. This study examines the use of TDA features in conducting state estimation of non-stationary systems, with the intend to produce advances enabling applications to high-rate systems. Specifically, the study focuses on identifying a moving boundary condition on a fixed roller beam by analyzing the system's frequency. A strategy to construct point clouds from collected time series measurements is defined by applying the Embedding theorem with time delays that are dependent on the system's minimum and maximum frequencies. After, a method to apply TDA feature extraction to nonstationary systems is proposed that employs a set of two sliding windows that also depend on the system's minimum and maximum frequencies. Then, principal TDA features applicable to point cloud data are evaluated from a physical perspective to determine their applicability to the high-rate state estimation problem. The maximum persistence of homology groups is identified as a set of key TDA features, and are applied to laboratory datasets obtained from the DROPBEAR (Dynamic Reproduction of Projectile in Ballistic Environments for Advanced Research) testbed. Results obtained on laboratory that demonstrate that the maximum persistence of H0 and H1 can provide a stable estimation of the cart location and have a lower noise level than other TDA features, with the maximum persistence of H1 outperforming H0. The maximum persistence of H2 was shown to be useful at detecting noise created by impact loads. Results also indicate that TDA feature can be used to track the cart location within an acceptable range and performs similarly or better than a Short-Time Fourier Transform for more rapid dynamics, thus showing promise for high-rate applications.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROPOSALS FOR NEW INNOVATIVE DESIGN LAYOUTS FOR VERTICAL TAKE-OFF AND LANDING AIRCRAFTS

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ABSTRACT

The structural concept of an aircraft having the possibility of vertical take-off and landing is motivated mainly by many useful and operational considerations. Helicopters and other innovative solutions of aviation structures, like for instance McDonnell Douglas/British Aerospace Harrier or Bell-Boeing V-22 Osprey [1], enable the effective implementation of such a task. Most of the currently used powered-lifts have relatively small cruising speeds and thus also small values of possible maximum speeds. The essence of the proposed structural systems is to enable the plane for vertical take-off and landing to reach relatively high maximum speeds. This goal is achieved due to the appropriate spatial arrangement of the components of the aircraft support structure and propulsion components, as well as the procedure for the transition from vertical to level flight back [2,3]. For the vertical take-off and landing, a propulsion system is used, which source is located in the immediate vicinity of the center of gravity of the entire aircraft then, thanks to the use of appropriate technical solutions, it does not take part in the subsequent, mainly horizontal phases of flight. Another propulsion system is used to give the airplane flight directions different than the vertical one. The power source for both systems can be the same engine or a set of piston engines, turbo-shaft or turbojet engines. The components of the structural system of such an airplane may take forms similar to those presently used in the supporting structures of various types of aircrafts. At least three different proposals for new innovative design systems for VTOL aircraft will be presented.

The proposed types of the structural systems of the vertical take-off and landing aircrafts require a number of comprehensive analyzes and tests to determine, inter alia, its economic efficiency and practical suitability for the indicated purpose.

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Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DAMAGE ANALYSIS OF HYDRAULIC CONCRETE BASED ON MODIFIED DISSIPATED ENERGY

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ABSTRACT

Energy dissipation is the essential property of concrete deformation and failure. It is a feasible way to study the failure of quasi-brittle materials such as rock mass and concrete with energy. However, the existing damage analysis results which define the damage variable by energy are not consistent with the actual damage evolution process of concrete. In this paper, it is considered that the damage of concrete is not caused by all the dissipated energy, but a part of it. Therefore, the dissipated energy is divided into two parts, one is the dissipated energy that causes concrete damage, and the other is the other energy dissipation during the functional transformation process of concrete under loads. The damage energy dissipation correction coefficient λ is introduced, and the damage variable is defined. The λ value is determined according to the measured test curve, and the damage evolution equation is established. The damage analysis results of the measured test curve show that the concrete damage evolution process using this method is more consistent with the test curve. The method is applied to the stress-strain curve given in the hydraulic concrete specification, which can reveal the change law of damage variable and equivalent plastic strain during the damage evolution of hydraulic concrete. The Method provides a feasible way to carry out damage analysis of hydraulic concrete.

Keywords：damage variable; dissipated energy; damage energy dissipation correction coefficient; hydraulic concrete; damage analysis

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Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL COMPUTATIONAL APPROACH FOR PREDICTING MICRO-BUCKLING SENSITIVITIES IN ARCHITECTED MATERIALS

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ABSTRACT

Architected Materials (AMs) have attracted attention due to their superior properties and functionalities obtained by exploiting elastic micro-buckling. However, the widespread adoption of AMs has been limited by the difficulty in predicting the onset of micro-buckling, which is highly sensitive to defects and imperfections. Current numerical models for analyzing and designing AMs are deterministic and do not account for unintended imperfections, leading to a lack of confidence in their performance. To address this issue, we present a new computational framework based on Hypercomplex Automatic Differentiation (HYPAD) that allows us to quantify local sensitivities in the onset of instabilities and post-buckling behavior of architected materials. In this talk, we will introduce this method to analyze the sensitivities of discrete structures exhibiting snap-through behavior and continuum elements such as geometrically non-linear shells. Our approach provides insights into the most significant factors affecting the onset of buckling and post-buckling behavior of AMs, enabling the development of surrogate models for uncertainty quantification and accounting for unavoidable uncertainties derived from fabrication, assembly, and actuation.

Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ONLINE PARAMETRIC GAUSSIAN PROCESS REGRESSION

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ABSTRACT

One of the limitations of using non-parametric Gaussian processes for prediction is their computational cost in handling streaming data, which becomes gradually available and grows in volume over time. To address this issue, we propose a parametric online Gaussian process regression (POGPR) algorithm that avoids the need to retain previous data, and instead focuses on a few parameters while incorporating new data. Our proposed algorithm is initialized with a dataset that optimizes the outputs for a set of hypothetical points. The hypothetical points are determined using a clustering algorithm combined with a hyper-reduced basis algorithm. These points, in conjunction with the hyperparameters, are then updated upon the arrival of new data, resulting in computational efficiency, as only the hyperparameters and the hypothetical data are used to handle the new data. To demonstrate the efficiency of POGPR, we present several examples, including a toy example involving the sine function, forecasting sea surface temperature in Cape Cod, and predicting airline delays. The results highlight that the proposed algorithm is efficient and capable of handling streaming big data.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AERO-HYDRO-GEOTECHNICAL REAL-TIME HYBRID SIMULATION OF MONOPILE OFFSHORE WIND TURBINE STRUCTURES UNDER OPERATIONAL AND EXTREME CONDITIONS

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Arindam Banerjee[1], *Justin Jaworski*[2], *Thomas Marullo*[1], *Kevin Wyckoff*[1] *and Liam Magargal*[1]

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ABSTRACT

Real-time hybrid simulation (RTHS) divides a structural system into an analytical and experimental substructure. The former is based on a well-established analytical model while the latter consists of a physical model placed in the laboratory, where for the latter a well-established analytical model is nonexistent. This study extends real-time hybrid simulation to monopile-type Offshore Wind Turbines (OWTs) to enable the accurate investigation of their behavior under operational and more severe conditions, considering the effects of aeroelastic and hydrodynamic loading along with soil-structure interaction. The embedded foundation of a monopile OWT is difficult to analytically model due to the complex behavior associated with the nonlinearities developed in the surrounding soil. Yet, the accurate modeling of the pile foundation subsystem is critical in order to acquire an accurate response determination of the OWT system under operational and extreme conditions. Consequently, in the RTHS approach presented herein the embedded foundation and surrounding soil of the OWT are modeled physically in the laboratory using a soil box while the remaining parts of the system and the aerodynamic and hydrodynamic loadings are modeled analytically. The program OpenFAST, developed by the National Renewable Energy Laboratory (NREL), is linked to the RTHS coordinator to determine the hydrodynamic and aerodynamic loads acting on the OWT, along with modeling the dynamics of the electric power generation equipment and associated controller for the OWT. The RTHS framework includes the dissipative unconditionally stable MKR-alpha integration algorithm to integrate the equations of motion, solution techniques used to enforce displacement compatibility at the interface between the OWT tower finite element model and the turbine blades' aeroelastic model, and numerical stability associated with the interaction between the integration algorithm and the hydrodynamic load computation. RTHSs of a 5 MW OWT subjected to operational and more severe conditions are performed to experimentally validate the framework.

The presentation will describe the recently commissioned Lehigh University Department of Energy (DOE) Offshore Wind Turbine RTHS Facility and the RTHS framework that has been integrated into the facility's real-time integrated control IT architecture. Results from using the framework to perform RTHS of a fixed monopile OWT under operational and extreme conditions are presented. Comparisons between RTHS where the soil-foundation system is modeled analytically to those where the pile-foundation system is modeled physically in the experimental substructure are presented, illustrating the significant amount of discrepancy in the results that occur when the soil is improperly modeled analytically.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE ELEMENT INVESTIGATION OF CRITICAL STATE SOIL FABRIC

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ABSTRACT

The theory of critical state soil mechanics (CSSM) has long described how soils at sufficiently large shear strains attain a constant mean stress, shear stress, and porosity under sustained shearing. This theory applies from a continuum perspective that does not directly consider the discontinuous particulate nature of real soils. The rearrangement and reorientation of grains associated with the attainment of the critical state suggests that unique fabric characteristics must also exist at critical state. Fabric herein refers to the packing structure of a granular medium, the orientations of individual grains, and the network of contact forces between grains, as well as any other factors that describe the combined soil skeleton and pore network. This study uses the discrete element method in three dimensions to investigate the granular fabric at large strains in a suite of simple shear simulations with different initial porosities and different particle shapes (i.e., particle aspect ratios of 1.0, 1.5, 2.0, and 2.5). The simulations further vary by how the individual grains are initially oriented relative to the direction of the prescribed shear velocity. With the aid of high-performance computing, over 200 simulations were performed, each with at least 100,000 particles. The initial porosity, grain shape, and grain orientations strongly affect the stress-strain-volume change behavior of the soils, and particle assemblages of the same shapes achieved consistent porosities at large strains, which is expected based on CSSM. The novelty of the findings in this study is that the long axes of the grains themselves and the contact orientations tended to achieve a consistent constant orientation relative to the shear direction that was independent of the initial grain orientation but dependent on the grain shape. Analysis of the fabric tensors in each simulation shows that the magnitudes of the major contact normal fabric and the inclination of their orientations from the direction of shearing systematically increased with the grain aspect ratio. The magnitudes of the major long-axis grain orientation fabric and the inclination of their orientations from the direction of shearing, on the other hand, systematically increased with a decrease in grain aspect ratio. The insights into critical state grain orientation and contact orientation are unique to the approach in this study, since these granular-level details cannot be elucidated in more traditional continuum models.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DERIVATION OF WAVE SPEED FOR DRY AND SATURATED NONLINEARLY ELASTIC MODELS

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ABSTRACT

Elastic wave speeds are crucial in geomechanics for measuring elastic stiffness. Traditionally, these speeds are calculated using an analytic formula based on a linearly elastic solid medium. However, empirical evidence suggests that stiffness is state-dependent [1], creating a mismatch between the theoretical assumptions and the observed stiffness constants. Recent advancements have addressed this gap by deriving wave speeds for hyperelastic (energy conserving) and hypoelastic (non-energy-conserving) constitutive models that are dependent on pressure and density [2]. These new derivations align with conventional empirical findings for isotropic states. However, the hyperelastic model predicts variations in the ratio of longitudinal to transverse wave speeds, as observed in experiments and discrete element simulations. This prediction emerges from energy-conservation terms in the model, eliminating the need for fabric assumptions previously considered in research. Our study expands on this by exploring various density-dependent relationships and extending wave speed calculations to saturated granular media. This research enhances our understanding of granular media stiffness in dry and saturated scenarios, offering new insights for interpreting wave speed experiments.

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Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LEVEL-SET ASSISTED ENRICHED IMMERSED BOUNDARY METHOD FOR STEFAN PROBLEM WITH APPLICATIONS TO ADDITIVE MANUFACTURING PROCESS

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ABSTRACT

Stefan problem is ubiquitous in many engineering problems such as welding, heat exchangers and additive manufacturing. However, it is challenging to solve Stefan problem involving the moving material interface with conventional numerical methods while preserving bounday accuracy and mesh flexibility. On the one hand, diffusive interface methods represent the interfacial surface with auxillary variables related to physical properties of the phenomenon. The auxillary variables and the physical properties don't have exact relationship in the most cases. On the other hand, sharp interface methods don't need the auxillary variables and represent the interface with the level-set field coupled with the boundary condition, but it is challenging to enforce Neumann and Dirichlet boundary contion on the interface at the same time. In this paper, we introduce the level-set assisted enriched immersed boundary method to track the fluid-solid interface and enforce boundary conditions accurately on the interface. The main features of the paper are generating the interfacial surface which is independent of the volumetric computational domain with a level-set field based on Neumann boundary condition for the fluid-solid interface and duplicates the DoFs at interfacial domain to enforce Dirichlet and Neumann boundary conditions. The enriched DoFs ensure the boundary conditions to be satisfied at the interface and to capture the interface. The results of the enriched immersed boundary methods for the metal solidification and laser melting for the Laser Powder Bed Fusion (LPBF) process outperforms compared to conventional immersed boundary methods and liquid fraction utilized diffusive interface methods to demonstrate the accuracy and the efficiency of the method. The potential development of the method for thermal multi-phase flow is discussed.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COUPLING EFFECTS OF FRAGILITY FIDELITY AND NETWORK RESOLUTION IN INFRASTRUCTURE RESILIENCE

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ABSTRACT

Inferring the performance of infrastructure systems under deterioration, extreme events, and recovery actions requires modeling the components and processes involved at different temporal and spatial scales, usually laden with uncertainties and interaction effects. Research efforts in this area have typically focused on developing accurate models at individual analysis scales (e.g. hazard estimation, damage prediction); however, less attention has been placed on the role of modeling errors when these routines are coupled for regional scale assessments. In this paper, we investigate how modeling errors arising from lack of fidelity (or representativeness) in damage and network models affect regional resilience estimations. First, the effects of undersampling structures' characteristics during fragility model fitting are evaluated. Acknowledging the role of network structure in the quality of performance metrics, we further evaluate network resolution as a source of modeling errors at a broader scale. Bridge fragility models and transportation networks are used as illustrative examples. We estimate the coupling effects over the quantities of interest (such as loss of connectivity or recovery trajectories) when models with varying resolution (i.e., representativeness error) are coupled. To objectively measure the impacts of scale-specific errors and those induced by coupling effects, we use different statistical distance metrics. Results show that deviances in resilience outcomes are correlated, as expected, with the 'level of error' in fidelity at individual scales. More importantly, coupling effects are found to be drivers of more complex errors at larger scales which may be highly tied to the interaction of the models' resolutions. We envision the intrinsic relationships between model resolution and their impacts on resilience-related metrics shown in this paper can guide the selection of the appropriate level of model representativeness, balancing out modeling errors with the required confidence and resolution in the quantities of interest.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RE-PROGRAMMABLE MORPHING THROUGH TUNABLE POISSON'S RATIO

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ABSTRACT

Shape morphing metamaterials can facilitate the design of a wide range of systems, including deployable structures, transformable robots, and biomedical devices. However, despite the advances in the field, each metamaterial architecture can shape into a single shape upon application of a given load. Reversibly transforming the structure's shape between a set of shapes remains an open challenge. In this work, we present a metamaterial that allows for re-programmable morphing. The structure comprises pairs of hinged rigid squares connected by rigid linear elements. The Poisson ratio of each unit can reversibly be switched between three values: negative, positive, and close to zero. We show that by programming different values of Poisson's ratio in the structure, 3D shapes with different Gaussian curvature can be realized upon application of combined bending and compression loading along one axis. The shape-shifting is reversible and the tuning of the Poisson's ratio can be easily controlled by a set of magnets. The intrinsic periodicity of the proposed design enables the realization of large structures (i.e. meter-scale) thus opening the possibility of realizing large shape-morphing systems with potential applications in aerospace structures, wearables, and architecture.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECENT ADVANCEMENTS ON THE AXIAL STRESS MEASUREMENT OF WELDED RAILS USING MECHANICAL VIBRATIONS

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ABSTRACT

Continuous welded rails (CWR) are track segments connected by weld joints. With respect to mechanically-jointed rails, CWR provide a smoother ride to passengers, can be traveled at higher speeds, require less maintenance, and have a longer life cycle. However, CWR are prone to buckling during warm seasons when high temperatures induce large compressive axial force in the rails. To prevent buckling and therefore derailments, rail owners enforce slow orders or even shut the lines temporarily. The best way to avoid such inconvenience is by estimating the temperature of the rail at which the rail may buckle, and this is related to the rail neutral temperature (RNT), which is the temperature of the rail steel at which the average stress across the rail cross-section is zero. The estimation of the RNT is currently achieved by labor-intensive and sometimes invasive methods. In the study presented in this paper, an in-situ nondestructive evaluation technique was investigated to estimate axial stress and RNT. As part of the study, a general finite element model of CWR under varying boundary conditions and axial stresses was developed to predict the natural frequencies of rail vibrations. The model was then validated experimentally and updated by testing a real track in the field. During the experiment, an instrumented hammer was used to trigger vibrations which were recorded with an array of wireless accelerometers. The power spectral densities of the accelerations were extracted and compared with numerical predictions to estimate the RNT using machine learning algorithms. The estimates were then compared with measurements conducted by a third independent party that used strain gages, showing very good agreement. In this paper, a discussion about the challenges and the outcomes of the generated physics-based finite element model is carried out.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONCURRENT ESTIMATION OF TIME-VARYING AND TIME-INVARIANT PARAMETERS IN NONLINEAR AEROELASTIC SYSTEMS

Brandon Robinson[1], Philippe Bisaillon[1], Mohammad Khalil[2], Chris Pettit[3], Dominique Poirel[4] and Abhijit Sarkar[1]*

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ABSTRACT

A Bayesian computational framework is presented which permits the robust joint estimation of system states, time-varying parameters and time-invariant parameters from noisy measurements of dynamical systems [1]. The framework leverages Markov chain Monte Carlo (MCMC) methods for the estimation of time-invariant system parameters, while relying on nonlinear filters to jointly estimate the system states and time-varying parameters. Despite the cost associated with MCMC, it offers a number of benefits which justify the incurred computational demand. Standard approaches for state and parameter estimation involve appending the parameters to the system states and using nonlinear filters to estimate the elements of this augmented state vector concurrently. In this work, only a subset of parameters of interest, being time-varying are included in this augmented state vector, while the time-invariant parameters are estimated using MCMC. This strategy limits the order of the augmented state space and reduces the strength of the nonlinearity in the augmented system dynamics. Critically, the use of MCMC also permits the Bayesian estimation of the process noise strength related to the model error and to the artificial dynamics of the time-varying parameters.

For numerical illustration, the framework is applied for damage detection of a pitching airfoil. The aerodynamic forces acting on the airfoil are functions of the pitch displacement, velocity and acceleration. Hence, the overall system mass, damping, and stiffness matrices comprise both structural and aerodynamic parameters. Recent works have demonstrated the effectiveness of sparse learning, specifically the nonlinear sparse Bayesian learning algorithm, for model selection using wind tunnel data [2]. Based on previous experiments, we generate synthetic data that mimics the observed behaviour of an undamaged airfoil, and jointly estimate the structural and aerodynamic parameters of the data-optimal model. A second set of data is generated which includes a sudden loss of structural stiffness. We then apply the Bayesian framework to estimate the time-invariant structural and aerodynamic parameters alongside the time-varying structural parameter(s).

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTALLY EXTENDING THE USEFUL STRAIN-RANGE OF UNIAXIAL TESTING OF SHEET METALS BEYOND THE LIMITS OF HOMOGENOUS DEFORMATION

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ABSTRACT

With the ever-increasing importance of reducing carbon emissions, the automotive industry maintains a particular interest in weight-reduction of both internal combustion engine and electric vehicles. This is achieved in part by light-weighting of formed sheet-metal components without compromise of structural integrity and safety. Core to this goal is understanding the stress response of these materials under the large deformations present during forming operations. The uniaxial tension test has long been the standard benchmark for generating constitutive models of metals, but the applicable deformation range of the technique is limited due to specimen necking that occurs beyond the ultimate tensile strength (UTS). For steel, local strains in the neck near fracture can exceed five times the UTS strain, but the post-UTS stress response is typically considered inaccessible to standard uniaxial testing equipment. Many numerical inverse methods have been developed to characterize the post-UTS stress-strain behavior, but these methods tend to suffer from complications regarding solution uniqueness, mesh-sensitivity, and the a priori assumption of a constitutive law. Using a combination of mechanical testing, digital image correlation (DIC), and in-situ x-ray diffraction (XRD), the multiaxial stress response in the neck can be determined experimentally. This allows true stress-strain curve measurement to much higher plastic strains than conventional methods allow. To obtain accurate stress tensors at large strain, the effects of texture evolution on the x-ray diffraction elastic constants are handled via careful stress factor (Fij) calibration. These data are being used to empirically validate various methods of post-UTS stress-strain extrapolation and develop criteria to aid standalone DIC systems with post-UTS stress-strain quantification. The unique combination of metrology available the NIST Center for Automotive Lightweighting (NCAL) is being used to modernize a classical, tried-and-true technique, ultimately providing means with which to extract significantly more constitutive data from traditional uniaxial test setups.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROBABILISTIC SENSITIVITY ANALYSIS IN OPTIMIZING OPERATIONAL CONDITIONS IN CO2 SEQUESTRATION USING NEURAL OPERATORS

Fernando Rochinha[1], Alvaro Coutinho[1], Rômulo Silva[1], Rodolfo Freitas[1], Gabriel Barros[1] and Ezequiel Santos[1]*

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ABSTRACT

Carbon Dioxide Capture and Storage (CCS) in underground reservoirs plays an important role in mitigating global warming. It represents one key technology to reduce the amount of CO2 in the atmosphere. It involves complex multi-phase flows within a subsurface heterogenous medium, and its operational optimization and design [1] rely on very expensive computational simulations. In order to cope with that, Scientific Machine Learning Surrogates [1] have been used, leading to affordable and accurate predictions on proper time. A critical component of reliable predictions is the ability to provide uncertainty quantification. The presence of unavoidable uncertainties, mainly linked to the complex geology (e.g., very heterogeneous permeability fields) not well characterized through indirect methods and data, makes the optimization problem still more complex [3]. Here, as a preliminary step, we present a sensitivity study regarding the impact of uncertainties in CCS effective indexes usually employed in operational conditions. The sensitivity study is only made viable through the intensive use of neural operators as surrogates of the original high-fidelity physics-based flow model.

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Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARISON OF THE PROBABILITY OF CONTENT OVERTURNING IN CONVENTIONAL STRUCTURES VERSUS STRUCTURES EQUIPPED WITH FLUID VISCOUS DAMPERS

José Rodríguez-Morales[1], Sonia Ruiz-Gómez[1], Ali Rodríguez-Castellanos[2] and Roberto Amparán-Ortega[1]*

[1]Universidad Nacional Autónoma de México
[2]Universidad Autónoma de Sinaloa

ABSTRACT

The structures considered essential are those whose functionality must be preserved following a significant seismic event or those experiencing considerably substantial indirect losses. Seismic design codes conceive these structures with a higher level of safety by considering a greater seismic force during their design phase. However, structural engineers have paid limited attention to the design of non-structural elements and content review, whose damages could significantly impact on both the operations of the structure and its repair costs. This study determines the probabilities of content overturning in structures by comparing two different types of structural systems for a mid-rise building: one structured with reinforced concrete frames and another integrating viscous dampers. Through nonlinear dynamic analyses associated with seismic events with return periods of 250 and 475 years, the probability of content overturning is estimated by treating them as rigid rectangular blocks excited by the absolute floor acceleration.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TAILORED GRÖBNER BASIS ANALYSIS OF THE REYNOLDS-AVERAGED NAVIER-STOKES EQUATIONS

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ABSTRACT

This work aims to investigate the cardinality and algebraic structure of Reynolds Averaged Navier Stokes (RANS) solutions through the application of a tailored algorithm based on Gröbner Basis. This analysis aims to contrast classical deterministic models with the solutions obtained as a distinctive characterization of turbulent models.

The algorithm, first proposed by Gerdt, Blinkov, Mozzhilkin in 2006, was originally intended for solving two-dimensional linear partial differential equations. It is based on converting the original PDEs into a discrete system and computing a Gröbner basis of the linear difference ideal generated by the resulting set of polynomials. However, Raynolds Averaged Navier Stokes (RANS) solutions comprise nonlinear, three-dimensional PDEs. This presents not only mathematical but also computational challenges, as the resulting difference system obtained is nonlinear, and integration contour grids significantly increase in complexity. To address this issue, there are two options: one is to define nonlinear terms as independent functions, a method Gerdt, Blinkov, Mozzhilkin proved viable with Burgers' nonlinear PDE. Alternatively, technological advances now allow the computation of complex, nonlinear polynomial systems using specialized python libraries.

Through this methodological framework, we aim to provide a unique insight into the nature of turbulent flow models contributing to the complex field of fluid dynamics.

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Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CLOSED-FORM SOLUTIONS FOR THE STOCHASTIC RESPONSE OF WIND-EXCITED STRUCTURAL SYSTEMS BASED ON INTEGER- AND NON-INTEGER-ORDER FILTER APPROXIMATIONS

Luca Roncallo[1], Ilias Mavromatis[2], Ioannis Kougioumtzoglou[2] and Federica Tubino[1]*

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ABSTRACT

A filter approach is developed for approximating wind excitation power spectra and for determining efficiently the stochastic response of linear structural systems. Specifically, first, an integer-order filter model is employed for approximating a commonly used atmospheric turbulence power spectrum [1]. Next, it is shown that the integer-order filter approximation enables the analytical evaluation of pertinent random vibration integrals for determining in closed-form the response statistics of a linear oscillator subjected to the atmospheric turbulence power spectrum; see also [2] for some indicative relevant applications. Further, a non-integer-order filter model is also used for approximating the atmospheric turbulence power spectrum. It is shown that this model exhibits a higher degree of accuracy in approximating the power spectrum in the frequency domain compared to the integer-order filter. Furthermore, it allows for approximate analytical calculation of linear oscillator response statistics based on an appropriate state-variable formulation [3].

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INFRASTRUCTURE RESILIENCE QUANTIFICATION FOR DEVELOPING SEISMIC MITIGATION POLICIES AND RECOVERY PLANNING

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ABSTRACT

Earthquakes worldwide have caused significant damage to the built environment and resulted in high economic losses. Recent earthquakes, such as the 2023 Kahramanshah earthquake in Turkey, emphasized the importance of communities' resilience plans to effectively mitigate and recover from these natural disasters. To achieve this, it is crucial to quantify metrics using available community-level data and information for informed decision-making and planning. In this study, the authors present a methodology for quantifying the seismic resilience of community systems, including physical and economic systems. The results of this process can assist decision-makers in implementing mitigation policies to improve the immediate response and recovery of earthquake-prone communities. The methodology involves combining engineering and economic models to develop a comprehensive resilience quantification model. The engineering model incorporates earthquake shake and liquefaction hazard models to assess the physical damage and evaluate the repair cost, recovery time, and functionality of individual buildings based on fragility-based damage assessment. The economic model utilizes a spatial computable general equilibrium (SCGE) model, aggregating commercial buildings into sectors (e.g. retail, manufacturing, services) and categorizing residential buildings into various household groups. This model helps assess the economic losses within a community caused by scenario earthquakes. By integrating these models, the resilience model provides metrics that can be used to investigate different mitigation actions and help communities achieve their resilience objectives. The effectiveness of the proposed approach is evaluated through a case study conducted in partnership with Salt Lake County (SLC), Utah.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DENSITY RELAXATION IN TAPPED GRANULAR SYSTEMS: RECURRENT NEURAL NETWORK MODEL

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ABSTRACT

We report on simulations of microstructure development in assemblies of monodisperse spheres in a tapped container modeled through discrete element simulations. The average solids fraction of an assembly was computed at a tap completion when its kinetic energy was essentially zero. An ensemble of 25 realizations was evolved over the span of M=15,000 taps from which evolution curves of the solids fractions were obtained. Drastically different progressions of the individual realizations were observed that featured sporadic jumps in solids fraction over the duration of a small number of taps. This behavior is consistent with a collective reorganization process that has been previously reported in the literature. Visualizations further revealed the formation of crystalline regions separated by dislocations facilitating bulk sliding motion in the system through periodic boundaries. Simulations conducted at a higher tap acceleration promoted a larger frequency of jumps in density over the M taps, resulting in more of the realizations attaining an apparent final saturation density.

A recurrent neural network model developed with a 60% training set was used to forecast the ensemble-averaged density in the limit of a large number of taps. The model appeared to be able to capture jumps exhibited in the simulations beyond the training set. Our findings suggest that it may be possible to analyze the evolution of granular microstructure by applying deep learning methods. The inclusion of physics-informed quantities into the learning feature space may provide an enhanced ability to understand the process towards the development of predictive surrogate models.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMIZING HEAT DISSIPATION IN UNDERGROUND POWER CABLE DUCT BANKS USING DIFFERENTIABLE PROGRAMMING AND BAYESIAN OPTIMIZATION

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ABSTRACT

Optimizing the design of backfill material for duct banks is crucial for enhancing the thermal efficiency of underground power cables. The ambient temperature and heat generated by adjacent cables significantly impact their current carrying capacity and longevity. Traditional IEC 60287-based designs often neglect the convective heat dissipation through the soil, leading to suboptimal, wide cable spacings focusing solely on conductive heat transfer. This research aims to develop a novel optimization algorithm for designing both cable spacing and backfill material properties.

Optimizing cable spacing and backfill material properties presents significant challenges due to the non-linear interaction between thermal and hydraulic properties, such as diffusivity and permeability. Furthermore, the cable spacing affects both conduction and alters the convection currents in soil, resulting in a multi-dimensional optimization problem. Traditional finite-difference forward solvers present limitations in optimizing duct bank design, primarily because they do not inherently provide the gradient information necessary for optimization.

To address this challenge, we employ differentiable programming by integrating automatic differentiation to calculate the gradients of the objective function concerning the input parameters and optimize it through a second-order gradient-based optimization scheme, thus enabling a more efficient design of the backfill soil permeability and cable spacing. We demonstrate the application of differentiable programming in two scenarios: (a) optimizing backfill permeability given a target heat distribution and specific cable spacing and (b) optimizing cable spacing for a predefined backfill and target temperature profile. For instance, while adjusting the cable spacing to achieve optimal heat distribution for a backfill soil permeability of 1e-11 m^2, Bayesian optimization yields an optimal offset of 0.0398 m (target of 0.04 m), resulting in a relative error of 20.35% in the predicted heat distribution.

We compare the efficiency of differentiable programming in design optimization with the derivative-free Bayesian optimization algorithm. Gradient-based optimization is efficient for differentiable objectives but can get stuck in local optima. In contrast, Bayesian optimization is more global and can handle non-differentiable objectives using probabilistic surrogate models. By visualizing the loss landscapes showcase, we emphasize the necessity of complementing gradient-based techniques with global search methods to overcome local optima. This research provides valuable insights into optimizing heat in underground duct banks, ultimately enhancing the efficiency and reliability of power distribution networks.

EXPERIMENTAL VALIDATION AND MECHANICAL CHARACTERIZATION OF ADDITIVELY MANUFACTURED LATTICE-CORE BEAMS WITH DIGITAL IMAGE CORRELATION

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[1]The Pennsylvania State University

ABSTRACT

Advances in additive manufacturing technology have enabled the rapid construction of complex structures. Lattice structures are self-supporting intricate geometries that expend little to no excess supporting material through 3D printing processes. The mechanical properties for additively manufactured lattice beams must be investigated experimentally at small scale before evaluating designs for large scale. Prior computational simulations show the effectiveness of Law of Similitude to evaluate performance at various scales. This research aims to validate the performance experimentally to determine the mechanical properties of additively manufactured lattice-core beams such as the Gyroid, Diamond, and Fluorite lattices. While the standards for testing such structures do not exist, this experiment analyzes the behavior of each lattice beam under static loading conditions by applying digital image correlation software. The experimental tests in this study include the cantilever bend, three-point bend, and compression test. The open source Ncorr digital image tracking software is applied to each image sequence to capture the deformation and stress characteristics. The 2D tracking algorithms extract the relevant Euclidean strain fields for each test sample. The experimental data is compared with computational numerical simulations. The results of this investigation provide foundational work toward future understanding of complex dynamics of additively manufactured building components and structures subjected to environmental loading.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THERMO-MECHANICS OF GRANULAR MATERIALS: EXPERIMENTS AND SIMULATIONS

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ABSTRACT

Over the past 50 years, numerous investigations have shown that the application of cycles of heating and cooling to granular materials causes permanent densification through irreversible deformations associated with particle rearrangements. Due to such microstructural changes, applying thermal cycles can significantly change the structure and properties of granular materials as they are inherently linked. Despite many advances in understanding the impacts of thermal cycles on the physics of granular materials, evidence about the changes in their properties due to thermal cycles remains scarce.

The objective of this work is to assess the processing-structure-property relationship in granular materials subjected to thermal cycling. This subject is addressed by gathering the results of recent experiments and computations. Thermal cycling of rounded, subangular, and angular sands subjected to constant vertical stress under loose and dense states is performed in oedometric conditions. Coupled thermo-mechanical discrete element simulations are employed under similar conditions to provide complementary information on this problem. The analyses expand on the microstructural changes caused by thermal cycling and the interconnected impacts on the macroscopic physical properties of the studied materials.

Thermally induced densification is observed experimentally to be more significant for more rounded particles. The microstructural changes probed numerically reveal an increase in coordination number, an increase in fabric anisotropy, and important horizontal stress relaxation. Granular topology evolves non-monotonically and presents a maximum for a critical temperature amplitude, indicative of an optimal microscopic reorganization. Consequently, mechanical stiffness changes depending on fabric anisotropy and substantially increases in the vertical direction. Thermal conductivity correlates with the coordination number and peaks at the critical temperature amplitude. Intrinsic permeability to fluid flow decreases isotropically and monotonically with the amplitude and number of thermal cycles due to pore volume reduction.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEURAL NETWORK DISCRETIZATION FOR THE PHASE FIELD MODEL OF FRACTURE

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ABSTRACT

Phase field models have emerged as a popular and appealing technique to model damage and fracture in diverse material systems. Through the introduction of a scalar damage field and straightforward modifications to the variational form of the governing equations of elasticity, the displacement and damage response of a body can be modeled for many constitutive behaviors in the small and large strain regimes. However, phase field models require the introduction of a length scale parameter to smear the crack over a region of finite measure. Typically, these models are implemented with traditional finite element discretizations, and if the finite element mesh is not sufficiently refined in the vicinity of the crack, spurious length scale effects can be introduced to the problem. In this work, we explore using a mesh-free neural network discretization of the displacement and phase field to solve fracture problems. Neural networks are known to be universal function approximators, and because they depend nonlinearly on their degrees of freedom (weights and biases), they can be thought of as a class of adaptive spectral methods. Adaptive methods, where both the coefficients and the shape functions in the discretization are learned simultaneously, are of interest in fracture mechanics because of the localized behavior of a crack, whose position is not known a priori. Specifically, we focus on the weak form of the governing equations of the phase field model, which promises more natural boundary condition enforcement than strong form collocation methods. Existing techniques for weak form neural network discretizations are explored and extended to investigate their efficacy in the context of computational damage modeling.

SEISMIC RELIABILITY ANALYSIS OF STRUCTURES BY AN ACTIVE LEARNING-BASED ADAPTIVE SPARSE BAYESIAN REGRESSION APPROACH

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ABSTRACT

Seismic reliability analysis (SRA) of structure is basically a time-varying reliability analysis problem where one needs to integrate the effect of stochastic nature of earthquakes and uncertainty of various structural parameters. In this regard, the Monte Carlo simulation (MCS) technique is noted to be quite simple in concept and the most accurate for estimating the probability that the seismic demand of a structure exceeds its capacity for the target hazard level over the entire duration of the considered earthquakes. However, the approach needs to execute a large number of repetitive nonlinear dynamic response analyses of structures to obtain seismic responses. Metamodeling technique has emerged as a viable alternative technique to alleviate such computational burden while retaining the maximum possible accuracy. In SRA, the dual metamodeling approach is typically adopted to deal with stochastic nature of earthquakes. However, this approach assumes that seismic responses of different earthquakes follow a lognormal distribution. On the contrary, a direct metamodeling approach where separate metamodels are constructed for approximating responses of each earthquake avoids such prior assumptions. Though adaptive training near the limit state is important in the metamodeling-based reliability analysis, its implementation is quite challenging for both the conventional dual metamodeling and direct metamodeling approaches due to the record-to-record variation of earthquakes. Recently, an active learning-based adaptive Kriging metamodeling approach has been developed, but it relies on the lognormal assumption. Thus, an active learning-based direct metamodeling approach is important without the prior distribution assumption. In this context, an adaptive sparse Bayesian regression-based direct metamodeling approach is proposed for SRA. In the present study, an active learning-based algorithm is developed for adaptive training of metamodels to approximate different earthquakes' responses. In this regard, it can be noted that sparse Bayesian regression is computationally faster than Kriging due to the sparsity involved in sparse Bayesian learning. Thereby, the overall performance of the proposed approach is expected to be better than the existing adaptive Kriging approach in terms of both accuracy and computational cost. The effectiveness of the proposed approach is illustrated by numerical examples of SRA.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELING FRACTURE IN QUASI-BRITTLE MATERIAL USING A NOVEL MICRO-SCALE COHESIVE ZONE APPROACH INCORPORATING MICROCRACK/POROSITY INDUCED TOUGHNESS DEGRADATION

Samit Roy[1]

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ABSTRACT

In this era of additive manufacturing (AM), micro-scale manufacturing flaws and/or porosity can play a very significant role in the final fracture properties of the additively manufactured structure. With this as the motivating facor, the problem studied in this paper concerns the analytical estimation of the effect of microcracking and/or porosity on initiation fracture toughness in brittle solids. It should be noted that the presence of micro crack and/or pores near a macro-scale crack tip results in two distinct effects: (a) crack tip shielding due to decreased local modulus, and (b) local toughness degradation near the crack tip due to the presence of micro-damage [1]. Hence, these are counter-balancing effects of toughness degradation and crack-tip shielding due to microcracking. In this paper, crack growth initiation by coalescence of the macro-crack with pre-existing microcracks is studied with the aid of a novel cohesive zone model. Using this model, it is shown in a quantifiable manner that the both the size and the volume fraction of the micro-cracks and/or pores play a very significant role in reducing the fracture toughness in a quasi-brittle material. The effect of tri-axial constraint due to bi-material interface on the cohesive traction–separation law, and on the toughness value is also investigated and quantified. The effect of crack-tip shielding will be addressed in a future paper.

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Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE USE OF PHYSICS INFORMED NEURAL NETWORKS (PINNS) TO SOLVE INVERSE PROBLEMS IN HETEROGENEOUS MATERIALS

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ABSTRACT

Inverse problems involve determining material properties, external boundary conditions, and even hidden physics based on previously known field variable data. These problems have various applications in geomechanics, including flow through porous media, geological carbon storage, reservoir stimulation, etc. Given the high heterogeneity of the geological subsurface, determining the interface topology is part of parameter identification, with this information becoming available only afterward.

Traditional methods for solving inverse problems entail employing a forward solver, such as the finite element method, in each iteration. This process involves updating the necessary parameters to minimize discrepancies between the forward solver result and the provided data, making these methods computationally expensive.

Recently, a novel class of methods known as physics informed neural networks has been developed [1]. Compared with traditional finite element solvers, these methods could potentially lower computational costs for inverse problems. Although PINNs have been applied to relatively simple inverse problems in the past, the problem of material parameter identification with an apriori unknown interface is yet to be explored with these methods. Here, we solve the problem for more general cases with an arbitrary interface topology, where our objective will be to determine the material properties and interface shape from the known data of primary variables. This is accomplished through a composite neural network (CNN) framework with distinct neural networks for field variables and material properties in each material that employ identical activation functions but are trained separately for all other parameters. Additionally, for a priori unknown interfaces, additional trainable variables that represent the coordinates of points on the interface are provided to the neural networks. The interface topology is obtained from these trained coordinates through a piecewise linear approximation. The interface shape changes with each iteration, and, as a result, the inputs to the neural networks within each material (collocation points) are also updated in every iteration. The proposed framework [2] is evaluated through tests on several one-dimensional and two-dimensional inverse problems, utilizing manufactured solutions.

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Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT COMPUTATION FRAMEWORK FOR RECURRENT IDENTIFICATION OF BANDGAPS IN METAMATERIALS

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ABSTRACT

With the ongoing advancements in metamaterial design for studying elastic wave propagation, the ability to swiftly iterate over different component parameter sets to understand their impact on the macrostructure's bandgap characteristics is increasingly important. Traditionally, designers had to modify the macrostructure, conduct the necessary calculations, and perform postprocessing to comprehend the effects of the changes.

Given the computational demands of numerical models for complex structures, methods have been devised to simplify the information needed in finite element analysis (FEA). Specifically, the use of component mode synthesis schemes has significantly reduced their numerical cost. For this study, the well-known and reliable Craig-Bampton method was chosen as the formulation for metamaterial design. This method segments the macrostructure in a series of substructures modeled using FEA, where the internal degrees of freedom are reduced using a modal projection, resulting in a macrostructure with a reduced number of degrees of freedom.

However, when a reanalysis of a macrostructure is required due to modifications in some of its characteristics, computational times can still grow significantly in assemblies with numerous substructures since each substructure needs to be re-analyzed (using FEA) and reduced (using Craig-Bampton).

This work proposes a framework to estimate bandgaps of a given metamaterial macrostructure without the need to re-run FEA after modifying its geometrical characteristics. Within this framework, the mass and stiffness matrices of the substructures are calculated for a nominal set of model parameters. Subsequently, any modification around the nominal parameters is accounted as a perturbation of this nominal configuration. In particular, the perturbed mass matrix is assumed to be equal to the nominal configuration, while the perturbed stiffness matrix is obtained by perturbing a nominal stiffness submatrix. This perturbed submatrix contains only the natural frequencies of the substructure at a fixed interface. A Kriging-based metamodel is adopted to establish a relationship between the model parameters and the mentioned natural frequencies to speed up the estimation of the perturbed stiffness matrix. After training the metamodel with a small set of model parameters (all around the nominal characteristics), obtaining the reduced stiffness matrix for a new set of model parameters is possible without re-running the FEA.

The precision of the proposed perturbation approach is compared against a high-fidelity solution based on FEA over three benchmark problems. Practical applications of this framework are mentioned, primarily focusing on its benefits for uncertainty quantification in manufacturing processes, where Monte Carlo simulations are commonly implemented.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROGRESSING STEREOPHOTOGRAMMETRY FOR EXPEDITED INSPECTION OF LARGE-SCALE STRUCTURES

Fabio Bottalico[1] and Alessandro Sabato[1]*

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ABSTRACT

In recent years, computer vision has been increasingly used for assessing the conditions of targeted structures thanks to advancements in computational power and a decrease in the cost of cameras. Among the numerous computer vision methods available, stereophotogrammetry techniques such as three-dimensional digital image correlation (3D-DIC) and three-dimensional point tracking (3D-DIC) are capable of extracting full-field displacements of structures by processing images acquired from synchronized stereo cameras and performing triangulation. The capability of extracting 3D displacements makes these techniques extremely useful for structural health monitoring and structural dynamics analyses. To reconstruct the 3D points in space, the stereo cameras must be calibrated to compute the lens distortion (i.e., intrinsic parameters) and the cameras' relative position and orientation (i.e., extrinsic parameters). At the same time, a stochastic pattern/optical targets must be applied to the structure being tested. Traditionally, calibration is performed by taking pictures of a calibration object, such as a checkerboard with dimensions comparable to the size of the tested structure. For large-scale structures, such as utility-scale wind turbine blades or bridges, calibrating the stereo cameras becomes a cumbersome and impractical procedure. Additionally, applying a stochastic speckle pattern/optical targets is not always feasible for real-world structures. These constraints limit the usability of stereophotogrammetry for condition monitoring of large-scale engineering systems. To increase the use of stereophotogrammetry in this domain, this research proposes i) the use of a novel multi-sensor system to compute the extrinsic parameters of a stereo vision system and streamline the calibration procedure and ii) a novel segmentation-based natural pattern tracking algorithm to eliminate the need for a patter/target. The experiments performed to characterize the accuracy of the two approaches are presented and discussed. In particular, the tests performed on large-scale structures show that the sensor-based calibration yields an accuracy greater than 95% compared to stereophotogrammetry measurements performed when a traditional image-based calibration is used. Also, the proposed natural pattern-tracking algorithm can reconstruct the 3D positions and displacements of features naturally present on the structure with an average accuracy above 98% in the X, Y, and Z directions. The results shown in this research prove how the proposed methods can be valid alternatives to traditional image-based calibration and speckle pattern tracking and can increase the applicability of stereophotogrammetry for monitoring large-scale structures.

Climate change, extreme weather events, and infrastructure resiliency
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LARGE-EDDY SIMULATIONS OF HURRICANE BOUNDARY LAYER TURBULENCE USING A HIGH-RESOLUTION WAVE-RESOLVING MODEL

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ABSTRACT

Hurricanes have caused the most damage among the natural disasters in the US by inflicting more than $1 trillion since 1980. This damage from hurricanes is primarily due to extreme winds and storm surges, which are produced by these massive weather systems. Many paramount fluid dynamical processes affect hurricane dynamics such as rotation, turbulence, and air-sea interactions. However, our understanding of these physical mechanisms that lead to the unique dynamics of hurricanes is poor due to the lack of sufficient measurement data and high-resolution simulations [1]. Without proper modeling of these physical processes, hurricane forecasts will not be accurate, and this inaccuracy can cause severe damage and economic losses.

In this presentation, we aim to bridge this knowledge gap by conducting a thorough sensitivity analysis of the hurricane boundary layer (HBL) using large-eddy simulation (LES). We will characterize the impacts of the radius, surface roughness, and gradient winds on the hurricane's mean and turbulence dynamics. Our results indicate that increasing the rotation increases the hurricane's maximum jet velocity, decreases the boundary layer height, and reduces the size of coherent turbulent structures at the same elevation [2]. Furthermore, we will show new high-resolution wave-resolving LESs of HBLs by varying the ocean wave height and wave ages. The results will be compared with dropsonde observations of wind profiles and the implications of different ocean wave characteristics on the surface wind of hurricanes will be presented. This study provides new insights into the turbulence dynamics in hurricanes and can guide the development of more accurate surface layer parameterizations of hurricane flows for enhanced weather/climate forecasts [3].

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Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHEMO-MECHANICAL COUPLINGS AT THE MICRO SCALE IN POROUS GEOMATERIALS

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ABSTRACT

The intricate interplay between chemical and mechanical processes in soil and rocks has emerged as a key factor to consider for many engineering applications like underground storage or geothermal energy or to understand geological processes like diagenesis or earthquake nucleation. Those reactions lead to mineral dissolution/precipitation that can modify the different properties of the rock. Those chemo-mechanical couplings have been investigated considering two main mechanisms.

A new campaign of Discrete Element Modelization (DEM) simulations has been carried out to investigate the effect of the debonding on the mechanical properties of the rock in oedometric conditions. Those simulations consider a cohesive granular sample, while the bonds are dissolved by acid injection. The influence of the degree of cementation, the initial state of stresses, the confining pressure or the loading history have been studied. It appears that the sample aims to reach an attractor configuration with the weathering and this evolution can lead to a stress redistribution when a reactive fluid is injected into a reservoir and eventually to induced seismicity.

A new coupling between a Phase-Field (PF) method and a Discrete Element Modelization (PFDEM) has been recently developed to investigate deeper on chemo-mechanical couplings. The grains are modelled in the DEM part as polygonal (2D)/polyhedral (3D) particles to capture their complex shapes as they influence greatly the macroscopic mechanical behavior of the material. Considering the granular material as a phase, PF is a good candidate to model with physics-based laws an addition or reduction of the quantity of material locally. The dissolution at the contact is controlled by the introduction of mechanical and chemical energy into the Allen-Cahn formulation on the phase variables, whereas the precipitation and the mass conservation are verified by a coupled diffusion formulation on the solute concentration. This method has been applied to reproduce results from previous works on the pressure-solution phenomenon at several grains level. Pressure-solution has a pivotal role in earthquake nucleation and recurrence or in diagenetic processes, among others. It involves three chemo-mechanical processes at the micro-scale: dissolution due to stress concentration at grain contacts, diffusive transport of dissolved mass from the contact to the pore space, and precipitation of the solute on the less stressed surface of the grains.

Sac-Morane, A., Veveakis, M., and Rattez, H. A phase-field discrete element method to study chemo-mechanical coupling in granular materials, under review in Comput. Methods in Appl. Mech. and Eng.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIMULATING THE CONE PENETRATION TEST IN UNSATURATED SOILS USING COUPLED DISCRETE ELEMENT METHOD AND MULTIPHASE LATTICE BOLTZMANN METHOD

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[1]Virginia Tech

ABSTRACT

The cone penetration test (CPT) is one of the most widely used site characterization techniques in geotechnical engineering. In this test, measurements of cone resistance, sleeve friction, and penetration pore pressure are correlated with engineering properties of the soil such as stiffness, shear strength, and in situ state. However, most of these correlations are developed for saturated soils, assuming either fully drained (no change in pore pressure) or fully undrained (no change in volume) conditions. In the more general case where the soil is unsaturated, it is not clear how the presence of suction affects the readings and how the distribution of two fluid phases affects the drainage conditions. In this study, we simulate the process of cone penetration in unsaturated granular materials using the Discrete Element Method coupled with the multiphase Lattice Boltzmann Method (multiphase LBM-DEM) to model the full hydro-mechanical response. We perform our analyses at different saturation levels, with a particular interest in saturation levels at which partial drainage occurs. We also consider different cone sizes, penetration velocities, grain size distributions, and packing densities. The particle- and pore-scale nature of the numerical method allows us to delve into the micromechanics of the problem. Particularly, we show how the pore fluid redistributes as the cone penetrates, how the pore water and pore air pressures change, and how these changes affect the readings. Not accounting for the effect of suction and the drainage conditions when analyzing CPT data in unsaturated soils can result in unconservative estimates of the soil properties, which become especially important if the CPT data is to be used for assessing the liquefaction potential of the site upon future saturation. While the main objective of this work is to develop a better understanding of the CPT, the findings of this study can be more generally applied to the problem of cavity expansion in wet porous materials.

Addressing uncertainties in infrastructure risk management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEISMIC PERFORMANCE AND RESIDUAL LIFE ANALYSIS OF CORRODED CONCRETE BRIDGES IN ITALY: A CASE STUDY

Shima Sadeghzadeh[1], Camillo Nuti[1] and Cristoforo Demartino[1]*

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ABSTRACT

The aging infrastructure of Italy's highway bridges leads to corrosion-related deterioration, subsequently heightening their vulnerability to seismic loads. This study presents an in-depth analysis of the probabilistic seismic performance of existing reinforced concrete bridge, specifically focusing on the impacts of corrosion. A parametric finite element model (FEM) in OpenSees of a simply supported bridge is initially established, incorporating data from a database that represents the structural characteristics of the bridge. Subsequently, the study integrates a probabilistic corrosion model into the FEM, simulating the time-variant degradation of steel reinforcement under varying environmental conditions at the cross-section level. Finally, monotonic static analyses are conducted, with the focus on evaluating the capacity-to-demand ratio as a time-dependent problem where the capacity is a decreasing function of time. The proposed framework is applied to a case study of an Italian simply supported reinforced concrete bridge built in Italy in the 1980s. The bridge spans nearly 1 km with 25 columns having different geometry, reinforcement, and heights and currently shows noticeable degradation due to rebar corrosion. The full paper will show results of these analyses highlighting the impact of corrosion on the residual nominal.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRACTURE RESPONSE OF BIOFIBER-REINFORCED CONCRETE (BIOFRC)

Amirreza Sadighi[1], Mohammad Houshmand[1], Ali Rahmaninezhad[1], Divya Kamireddi[1], Yaghoob Amir Farnam[1], Christopher Sales[1], Caroline Schauer[1] and Ahmad Najafi[1]*

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ABSTRACT

In this study, a numerical analysis has been conducted using phase-field fracture framework to predict the fracture response of a novel type of multi-functional fiber-reinforced concrete blocks [1, 2]. These multi-functional fibers, called BioFibers, have been coated with two layers [3]. The first layer is a bacteria-laden crosslinked sodium-alginate hydrogel, serving the self-healing purpose in the structure. The second layer, which is a polymer blend of polystyrene and polylactic acid (PLA:PS), is a robust damage-responsive self-healing activation strategy, also acting as a protective layer for unwanted release of self-healing agents. This added layer can also improve the interface properties of the fiber with concrete. In the case of crack propagation, the hydrogel will be exposed to water, swell, and release bacterial self-healing agents into the crack surface. This swollen hydrogel loses its mechanical integrity and turns from its initial tough form into a viscous material. Different reinforced concrete structures with different volume fractions and randomized distributions of BioFibers will be considered with the two different states of hydrogel; when untouched with brittle material properties, and when exposed with viscous material properties. Furthermore, by changing the copolymeric blend ratio of PLA:PS, different levels of toughness can be achieved for the outer coating, which can also impact the interface properties along with the crack resistance. Accordingly, different material mismatches will be considered for this coating in the finite element models. All the structures will undergo three loading conditions: tensile loading, compressive loading, and three-point bending, and in order to have means of comparison for the fracture response of these structures, the values of peak force and absorbed energy of each be taken into consideration. As expected, the mechanical and fracture response of the BioFiber-reinforced concrete (BioFRC) is greatly driven by the state of the hydrogel, as well as the material composition of the shell.

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Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT AND VERIFICATION OF A DATA CAPTURING ALGORITHM IN NEUROMORPHIC IMAGERS FOR COMPLEX EVENTS

Wyatt Saeger[1], Brandon Sisk[1], Duncan Gardner[1] and Fernando Moreu[1]*

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ABSTRACT

Computer vision has gained popularity in the fields of Structural Dynamics and Structural Health Monitoring (SHM) due to its potential to efficiently identify and quantify deflections, strains, cracks, and more. However, the physical properties of frame-based imagers, such as a limited frame rate, limit the capabilities of computer vision in extreme conditions. This limitation can be overcome through the use of Neuromorphic Imagers or Event-Based Vision (EBV). EBV uses event-based data capturing techniques instead of frame-based capturing techniques to greatly increase its temporal resolution and latency times. This study aims to evaluate the capabilities of neuromorphic imagers in capturing and quantifying unique events. The unique event types we will be looking into include combustion, high-speed rotations, and Real-Time Hybrid Simulation control applications. The DVXplorer mini Event-Based Imager created by iniVation is used to record the unique events and MATLAB is used to quantify the events. It is expected that the ability to quantify the events will depend greatly on the development of a new tracking algorithm. The data collected through these experiments can be compared to other sensors to observe the accuracy and robustness of the new algorithm. Through capturing unique events with a Neuromorphic Imager, this study facilitates the growth of computer vision applications in the fields of SHM and controls.

Uncertainty in geomechanical and geochemical processes: Their role on prediction of natural and engineered system behavior
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASSESSING RAINFALL-INDUCED SLOPE FAILURE FRAGILITY CURVES CONSIDERING THE EFFECT OF WATER EROSION BY A FEM HYDROMECHANICAL MODEL: CASE STUDY IN THE ROAD NETWORK OF BIOBÍO REGION - CHILE

Manuel Contreras-Jara[1], Esteban Sáez[1], Cristina Contreras[1], Juan de Dios Guzmán[1], Carlos Bonilla[21], Jorge Gironás[13], Alondra Chamorro[13] and Tomás Echaveguren[4]*

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ABSTRACT

Cut slopes are among the assets with the highest construction and maintenance costs for highways and roads. Their conservation over time guarantees the preservation of the road geometry and trafficability, since they are continuously exposed to natural and anthropogenic loads, extreme rainfall being the most relevant hydrometeorological event, destabilizing slopes and causing failures that can interrupt traffic and significant economic costs (Winter et al, 2013).

Intense and frequent precipitation events can induce slope instability (Xu et al., 2022). This is due to the infiltration of precipitation, which raises the groundwater level, increases the weight of the soil and water pressure, and decreases matrix suction in unsaturated soils. In addition, precipitation not only affects internal pressures on slopes, but also causes progressive degradation of the slope surface due to erosive effects (Navarro-Hevia et al., 2015). This erosion, in the long term, can alter the original soil conditions and increase the number of slope failures (Cheng et al., 2015). Currently, stability models do not consider this effect as part of the increase in slope failure vulnerability.

This research presents the development of fragility curves to represent the failure of cut slopes as a function of the total rainfall and the erosion rate of the slope. The stability was estimated by an hydromechanical model, using the finite element-based software Plaxis 2D, the uncertainty of rainfall was considered as a function of the fall pattern modeled with Huff rainfall distribution curves, the effect of erosion on slope stability was considered as a change in the shallow soil water retention properties as a variation in soil grain distribution by the removal of a fraction of the finest material.

Three cut slopes belonging to the road network of Biobío Region of Chile, were used as a case study. Soil profile, moisture and water table depth information was obtained from geophysical tests including seismic methods and electrical resistivity. Soil mechanical parameters and soil water retention properties were estimated from laboratory tests on unaltered samples. The rainfall of the June 2023 event with total rainfall of 150 mm in 24 hours was used to calibrate the models.

As a result, fragility curves were obtained that represent the probability of slope failure as a function of total rainfall. These results are useful for road maintenance managers to identify slopes that require erosion control or stability mitigation.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A GRIFFITH DESCRIPTION OF FRACTURE IN BRITTLE ELASTIC MATERIALS UNDER NON-MONOTONIC LOADING CONDITIONS WITH APPLICATION TO FATIGUE

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ABSTRACT

In this talk, I will present how the celebrated Griffith description of fracture nucleation from large pre-existing cracks and their subsequent propagation in nominally elastic brittle materials under monotonic quasi-static loading conditions can be generalized to non-monotonic loading conditions. The basic idea consists in considering the critical energy release rate Gc not as a material constant but as a material function of the loading history in conjunction with the identification of the regions around crack fronts where Gc evolves. Via direct comparisons with experiments on various ceramics and rocks under cyclic loading, I will show that the proposed formulation appears capable of accurately describing the fatigue behavior of nominally elastic brittle materials, in particular, their Paris law behavior. I will close with an outlook of the profound implications of the proposed framework on the description of fracture at large.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in mechanical energy harvesting and its applications in structural health monitoring and control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ANALYSIS OF PIEZOELECTRIC FIBERS REINFORCED COMPOSITES IN VIBRATIONAL ENERGY HARVESTING

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ABSTRACT

Over the years cantilevered piezoceramic beams have been frequently used as base-excited vibrational piezoelectric energy harvesters. In this article, we have analyzed the effectiveness of piezoceramic-based composites with d33 mode of actuation for enhanced energy generation from ambient vibration with a piezoelectric energy harvesting system. A finite element model-based electro-mechanical model has been developed and subsequently validated with existing experimental results for bimorph configuration. In this model, an improved shear and normal deformation theory have been used to accurately model the kinematics of deformation of the overall structure. Subsequently, the proposed model is used to analyze the effect of piezoelectric fiber orientation angle on the energy output of the overall system. It has been observed that vertically reinforced piezoelectric composites with d33 mode of actuation have the best performance.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ERROR-IN-CONSTITUTIVE RELATION (ECR) FRAMEWORK FOR THE WAVE-BASED CHARACTERIZATION OF LINEAR VISCOELASTIC SOLIDS

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ABSTRACT

To help investigate the spatiotemporal evolution of mechanical properties of mafic and ultramafic rocks caused by reactive flow underpinning mineral CO2 storage, we develop an error-in-constitutive-relation (ECR) approach toward the full-field characterization of viscoelastic solids described within the framework of standard generalized materials. To this end, we formulate the linear viscoelastic behavior in terms of the (Helmholtz) free energy potential and a dissipation potential. Assuming the availability of full-field interior kinematic data (as captured via e.g. laser Doppler vibrometry), the constitutive mismatch between the kinematic quantities (strains and internal thermodynamic variables) and their "stress" counterparts (Cauchy stress tensor and that of thermodynamic tensions), commonly referred to as the ECR functional, is established with the aid of Legendre-Fenchel gap functionals linking the thermodynamic potentials to their energetic conjugates. We then proceed by introducing the modified ECR (MECR) functional as a linear combination between its ECR parent and the kinematic data misfit, computed for a trial set of constitutive parameters. The affiliated stationarity conditions then yield two coupled evolution problems, namely (i) the forward evolution problem for the (trial) displacement field driven by the constitutive mismatch, and (ii) the backward evolution problem for the adjoint field driven by the data mismatch. This allows us to establish compact expressions for the MECR functional and its gradient with respect to the viscoelastic constitutive parameters. For generality, the formulation is established assuming both time-domain (i.e. transient) and frequency-domain data. We illustrate the developments in a two-dimensional setting by pursuing the multi-frequency MECR reconstruction of (i) piecewise-homogeneous standard linear solid, and (b) smoothly-varying Jeffreys viscoelastic material.

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FRAGILITY ASSESSMENT OF ANTICIPATORY AUTOMATIC SEISMIC TRIP SYSTEMS FOR CRITICAL FACILITIES

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ABSTRACT

Automatic seismic trip (AST) systems are intended to shut down specific equipment in critical facilities without human intervention if ground motions exceeding pre-specified tolerance levels occur at those facilities. Such systems could play an essential role in reducing the seismic risk of facilities like nuclear power plants, for which excessive vibration while operating could pose significant safety consequences. AST systems are designed to trigger a trip either during a strong motion or before its arrival, i.e., if they anticipate an ensuing ground motion exceeding a certain intensity threshold. The latter systems are herein referred to as anticipatory AST systems. To predict the intensity of an impending ground motion at a facility, anticipatory AST systems may either use the characteristics of the weaker primary (P-) waves arriving at that facility before the stronger secondary (S-) waves or rely on the ground motion data received at offsite stations.

Since shutting down critical facilities cannot happen immediately, an anticipatory AST system could be more effective than a non-anticipatory system in terms of seismic risk reduction since it acts before a damaging ground motion hits the facility. However, due to the inherent uncertainties of seismic waves and prediction algorithms, anticipatory AST systems may also lead to spurious trips, causing significant economic losses. As a result, probabilistic evaluation of anticipatory AST systems to quantify their seismic risk reduction benefits and the costs associated with their potential spurious trips is of paramount importance. Such an assessment can further help select potentially viable types of systems and set their performance objectives before designing the system for a particular facility. However, the lack of a straightforward yet robust methodology for these evaluations has hindered the vast application of anticipatory AST systems in critical facilities.

To tackle the above challenge, this presentation proposes a novel versatile methodology to develop fragility curves for any anticipatory AST system within any given seismological environment. The fragility curves characterize the probabilities of missed/late/spurious trips versus a ground motion intensity measure of interest. Using Monte Carlo simulations, the proposed methodology explicitly accounts for various independent/interdependent sources of uncertainty, including those associated with the system's design, equipment trip time, seismic waves, and seismic sources. Once the methodology is developed, its application is demonstrated by evaluating the performances of several alternative anticipatory AST systems for a hypothetical facility located in California in terms of the system's annual frequencies of errors and its seismic risk reduction benefits.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCEMENT LEARNING-BASED BRIDGE INSPECTION MANAGEMENT

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[1]*Purdue University*

ABSTRACT

Bridge health condition has long been an emphasis in civil engineering field and biannual inspections are required to assess the physical and functional condition of each bridge. Federal highway administration (FHWA) and department of transportation (DOT) in the United States continually updates specifications and techniques to normalize and advance the bridge inspection procedures. However, there are still ambiguous inspection requirements existing in the specifications due to lack of suitable optimization method. One of these requirements is relevant with inspection time arrangement. Currently, FHWA requires routine bridge inspection at least every two years and if necessary, inspectors can adjust the inspection frequency. The specifications don't outline the method of how to adjust the inspection frequency and thus in most situations, inspectors just determine new inspection frequency based on their experience. Another unclear requirement is how to use suitable inspection techniques. Many advanced techniques, e.g., ultrasonic surface wave and AI-based method, are applied to inspect bridges. These techniques own different features. Some of them provide high inspection accuracy while some of them are cheap and convenient to use. But the decision of using these techniques is relied on bridge inspectors' experience as no standardized decision-making process is defined in current bridge inspection specifications. Thus, this study focuses on developing a reinforcement learning-based method to assist inspectors in managing bridge inspection plan. In this method, reinforcement learning algorithm is utilized to optimize the frequency of inspection and the selection of inspection method. Due to lack of inspection data, a physics-based damage development model is utilized to simulate the deterioration process of the bridge. The reward function designed in reinforcement learning process considers both economic cost and inspection plan risk. After training, the reinforcement learning agent can rapidly determine optimal bridge inspection policy based on a bridge's state, which can minimize both the cost and the risk of bridge inspection work. Thus, inspectors can refer to this agent to make a specific inspection plan for each bridge based on a bridge's features. And in the future, the inspection specifications can also continue to complete relevant requirements based on the proposed method.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REAL-TIME HYBRID SIMULATION FOR INFRASTRUCTURE DEGRADATION ASSESSMENT: CONCEPTUAL FRAMEWORK AND APPLICATION EXAMPLE

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ABSTRACT

Real-time hybrid simulation (RTHS) is a disruptive technology that integrates numerical simulation and physical testing, simultaneously exploiting computational simulation methods and revealing unexpected physical behaviors from experimental components. This method is especially useful when the full experiment is not possible in a laboratory due to the size of the structure or the extreme conditions that must be realized, and simulation alone is insufficient to replicate complex loading conditions. Current applications of RTHS focus on assessing the effects that transient or short-term loads, such as earthquakes and wind, have on infrastructure systems. However, the effects of long-term or "wear-and-tear" loads, such as exposure to harmful environmental conditions or fatigue, have remained underexplored. This work presents a conceptual framework to assess the impact of long-term degradation on infrastructure systems. First, the non-degraded (nominal) state of the system is assessed through a series of RTHS experiments under the effect of short-term loads. Then, the partitioned nature of RTHS is leveraged by subjecting the physical specimen to different degradation levels through accelerated degradation techniques. At each degradation level, several short-term-load RTHS experiments are conducted to assess the behavior of the degraded system. If a previously defined failure threshold has not been reached, the physical specimen is submitted to accelerated degradation again and a new set of short-term-load RTHS experiments are conducted. Once the system meets the established failure criteria, the time-to-failure is recorded based on the level of degradation reached during the last accelerated degradation cycle. The same process is repeated for multiple physical specimens, and the time-to-failure of each specimen is recorded. Finally, a reliability-based approach is taken to determine the expected time-to-failure of the studied infrastructure system. The developed framework is demonstrated using a virtual nonlinear RTHS platform designed to test fiber-reinforced elastomeric isolators.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LOW-COST EFFICIENT INTELLIGENT WIRELESS SENSORS INCREASING HUMAN-DATA INTERFACES WITH THEIR ENVIRONMENT

Fernando Moreu[1], Mahsa Sanei[1], Morgan Merrill[1], Ali Khorasani[1], Kaveh Malek[1] and Gavin De Berry[1]*

[1]University of New Mexico

ABSTRACT

This presentation summarizes the efforts developing a new platform for sensing where the interface between the human and the value of data is enabled by the fabrication of the sensor. The theory is that fabricating the hardware and programming the software the user becomes engaged with the data. The research team has worked over the last nine years advancing a new sensing approach where grade school students can fabricate their sensors in less than fifteen minutes, and collect accelerations and use them to assess the quality of performance of structures, operations, and human activities. This presentation summarizes the evolution of the design, their uses in summer schools, in field applications, long term deployments, and learning outcomes and workforce development consequences associated with the new technology. The future efforts of this research is towards the advancement of curriculums, education, and workforce where the structural quantification is enabled by transferable technologies that can be built and changed in a few minutes by people without previous sensing, software, hardware experience.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL VALIDATION OF A VARIABLE INERTIA ROTATIONAL MECHANISM

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ABSTRACT

Rotational inertia mechanisms, which convert linear motion into rotational motion, can generate substantial mass effects and have potential for use in and as structural control devices. Recent advancements in rotational inertia mechanisms embrace devices with explicit nonlinearities, allowing them to exhibit variable behavior and performance across diverse load types and amplitudes. One such example is the variable inertia rotational mechanism (VIRM). The VIRM utilizes a flywheel with masses that can passively move within the flywheel, resulting in a flywheel with variable rotational inertia and a device that produces variable mass effects. Despite a number of studies on passive VIRM, experimental studies with passive VIRM are limited. This study aims to address this gap in knowledge by experimentally realizing a VIRM and using it to improve and validate a mathematical model of the VIRM. A custom-designed VIRM with a rack and pinion and a flywheel containing radially movable masses connected to springs was fabricated for this experimental investigation. The VIRM was then connected to a single-degree-of-freedom structure and subjected to various excitations using a shake table. Results of this experimental testing were used to update the mathematical model of the VIRM, and a separate set of experimental tests was then used to validate this updated model. This study contributes to the understanding of passive VIRMs and presents a validated numerical model of a VIRM for other researchers to utilize.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATING HUMAN-MACHINE COLLABORATION IN AUGMENTED REALITY-BASED BRIDGE INSPECTIONS

Alan Smith[1] and Rodrigo Sarlo[1]*

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ABSTRACT

Modern bridge inspection is a process which involves workers inspecting a bridge for damage, documenting their findings on pen and paper, and then transcribing these results into an online database. Augmented Reality (AR) emerges as a promising solution to streamline this data collection process, enabling real-time digital documentation and introducing automation via Machine Learning (ML). Current research predominantly explores AR and ML for virtual measurements and data visualization in controlled environments, often overlooking the crucial human elements in these workflows. This research aims to bridge this gap by evaluating an AR-based bridge inspection process, focusing on its efficiency, perceived workload, and system usability, thereby informing future developments in system design and the proper use of automation tools like ML.

Our research comprises two user studies. The first investigates the task of crack documentation in bridge inspection, encompassing measurements like height, width, and the largest crack opening. A conventional manual method, using rulers and pen-and-paper documentation, serves as the baseline. We developed four AR approaches with varying automation levels, ranging from minimal to fully automated, including two hybrid modalities. This study demonstrated that all AR versions lessened the perceived workload, matched the baseline in usability, and suggested a time-saving trend with increased automation. However, a fully automated approach indicated potential accuracy compromises. These findings informed the interface design for the second study, which involves ten bridge inspectors employing the AR system in real-world bridge inspections. This phase aims to assess the system's practical application and integrate AR and ML into bridge inspection workflows more holistically.

This research aligns with the minisymposium's focus on human-infrastructure interactions. It extends beyond the theoretical application of AR and ML in structural inspection by emphasizing the human operator's role and experience within this technological interface. Through this approach, we contribute to the understanding and enhancement of human-centric structural management, leveraging AR and ML technologies to optimize system performance, safety, and functionality in the field of bridge inspection.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING THE INFLUENCE OF PRE-EXISTING MICRO & MACRO CRACKS ON THE STIFFNESS OF BEAM STRUCTURES UNDER QUASISTATIC LOADING THROUGH PERIDYNAMICS

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[3]Indian Institute of Technology Guwahati

ABSTRACT

Structural integrity and performance are critical aspects in the design and operation of engineering structures. Pre-existing micro and macro cracks within materials are common occurrence, and understanding their impact on structural behavior is paramount for enhancing the reliability and safety of various engineering applications. This study delves into the complex interaction between micro/ marco cracks, and the stiffness of beam structures subjected to quasistatic loading, employing the innovative framework of peridynamics. This non-local continuum approach is used to simulate the dynamic interactions between particles within the material, allowing for the accurate representation of micro and macro cracks and their effects on the overall structural response. The investigation focuses on assessing the alterations in stiffness as a result of the presence of pre-existing micro/ marco cracks, providing insights into how these microscale defects influence the macroscopic behavior of beam structures. The study further aims to quantify the dependency of these effects on the size, density, and orientation of microcracks, contributing to a comprehensive understanding of the intricate relationship between microscale damage and macroscopic structural performance. The findings of this study not only advance the fundamental understanding of material behavior but also offer practical implications for the design and maintenance of structures, where the presence of microcracks may significantly impact the structural integrity. Ultimately, this research contributes to the broader field of structural engineering by providing valuable insights into effects of pre-existing cracks, enabling the development of more resilient and reliable engineering structures.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADDITIVE REPAIR OF CORRODED BRIDGE BEAMS: COLD SPRAY ADDITIVE MANUFACTURING

Brian Schagen[1], Wen Chen[1], Shengbiao Zhang[1], Haden Edward Quinlan[2], Anastasios John Hart[2] and Simos Gerasimidis[1]*

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ABSTRACT

In recent years the use of cold spray additive manufacturing applications has grown significantly due to the low working temperature, less product size limitations and one order of magnitude higher deposition rates compared to the established additive manufacturing techniques. This study discusses a new state-of-the-art application where cold spray additive manufacturing is introduced for additive repair of corroded bridge beams. The results highlight that repair by cold spray additive manufacturing can achieve significant capacity in comparison to the volume of metal added. Furthermore, near perfect capacity can be achieved and can even be surpassed depending on the additive material and corrosion profile, illustrating the promising potential for the use of cold spray additive manufacturing for repair of corroded bridge beams.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UPSCALING ARCHITECTED METAMATERIALS FOR APPLICATIONS IN CIVIL INFRASTRUCTURE USING ROBOTICS

Brian Schagen[1], Andreas Thoma[2], Matteo Pacher[2], Tanaya Bhave[2], Daniel Blank[2] and Simos Gerasimidis[1]*

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ABSTRACT

Currently, traditional construction methods are reaching their limits in terms of performance, growth, and defect rates. To overcome these challenges, the integration of robotics in the construction industry is considered a state-of-the-art innovation. Recent studies have explored the design and manufacturing of spatial structures through multi-robotic fabrication. Recent research has demonstrated that robotics can effectively create spatial structures with desirable structural behavior, flexibility, and efficient fabrication using manual welding. In this study, the process for designing and manufacturing an upscaled auxetic lattice using robotics is discussed. This includes challenges such as: working in a limited workspace, potential collisions, path planning requirements, and the need to find solutions within a defined space to successfully execute the fabrication process.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEISMIC FRAGILITY ANALYSIS USING MNARX MODELLING

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[1]ETH Zürich

ABSTRACT

Assessing the seismic vulnerability of civil structures is crucial for safeguarding human lives and ensuring the long-term functionality of essential infrastructure. Nevertheless, quantifying the capability of a structure to withstand a potentially large spectrum of seismic events still poses a significant challenge, due to the high level of uncertainty involved.

In the current state-of-the art, the uncertainty in the occurrence and magnitude of seismic events is modelled through a statistical ground-motion model (SGMM), which is then propagated through detailed computational models of the structure under investigation. Still, conducting Monte Carlo simulation using an SGMM model is often unfeasible on complex structures due to the high computational costs associated, e.g. due to high-resolution finite-element modelling (FEM).

To tackle this problem, surrogate models have emerged as computationally efficient proxies for FEM simulations. These models are trained on relatively small datasets, typically a few hundred to a thousand FEM simulations, and focus on mapping SGMM parameters directly to scalar building performance metrics, such as maximum interstory drift or other damage measures. Traditional surrogate models may however struggle to capture the stochastic nature of SGMMs, which exhibit significant latent variability. In other words, to each set of SGMM parameters corresponds an infinite number of ground motions. Additionally, these surrogates often provide only selected scalar properties of the time-dependent structural responses, rather than their complete time history.

To address these limitations, we propose to take advantage of the recently developed mNARX surrogate modelling strategy [1] to approximate the full history of the system response. mNARX offers two key advantages over traditional surrogates. First, it acts as an emulator for the full FEM, providing full-time history predictions, hence offering a deeper insight into the structural behavior. Second, it allows for incorporating prior knowledge of the physical system, through the construction of an exogenous input manifold, which results in exceptional data efficiency, significantly decreasing the training data needed with respect to traditional surrogates.

To illustrate the effectiveness of mNARX in seismic fragility analysis, we present a case study involving a three-story steel frame simulated using the open-source software OpenSees. The structure is exposed to real earthquake data from the PEER ground motion database. Our results show that the mNARX surrogate accurately emulates the quantities like the interstory drift, even when trained on very small datasets.

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Biological and biologically inspired materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANOBIOLOGICALLY REGULATED WOOD GROWTH PREDICTED BY MEANS OF A MICROMECHANICS-INFORMED BEAM MODEL

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[1]TU Wien

ABSTRACT

Mechanical stimuli strongly influence the growth of trees (or wood structures in general; resulting, e.g., from environmental forces or gravity. In particular, so-called reaction wood is formed, called compression wood in gymnosperms and tension wood in angiosperms. This way, the structure is able to control its posture by reinforcing and reorienting the axes of stems and branches, which is a key prerequisite for reaching large heights. The movement is due to asymmetric cambial activity resulting in eccentric growth and varying growth strains. The underlying biological mechanisms of growth strain generation are not yet fully understood. Nevertheless, several hypotheses correlating the induced macroscopic movement with the difference in cell wall structure of reaction and non-reaction wood have been proposed. On that basis, a homogenization procedure was developed for upscaling and evaluating the macroscopic effect of growth strains induced at the cell wall level. This contribution focuses on exploring the effect of the characteristic composition and microstructure of tension wood containing G-layers on the elastic properties and macroscopic growth strains by employing multiscale homogenization modeling techniques, based on the concept of continuum micromechanics. To that end, a multi-step homogenization scheme is employed to estimate the elastic properties of macroscopic wood based on the cell wall properties, the volume fractions of elementary components, and the organizational patterns at the considered hierarchical levels. The structural organization at the cell wall level is represented by multilayered cylindrical inclusions exhibiting transversely isotropic material behavior taking into account the previously evaluated layer properties depending on the composition of their elementary constituents, such as cellulose, hemicellulose, lignin and water. We derive the stress and strain fields corresponding to four different loading conditions, which allows for constructing the complete stiffness tensor of tension wood and upscaling the growth strains induced within the G-layer. Coupling the micromechanics model with non-linear beam mechanics structural model, applied to a growing branch inclined with respect to the vector of gravity, allows to simulate the reorientation process induced by growth strains at the cell wall level. In combination with experimental data of the branch shape evolution found in literature of specific species, growth-related parameters can be deduced, which may lead, in further consequence, to a better understanding and predictability of the growth process.

Advances and applications of elasticity within applied mechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DIE SWELL OF RUBBER: A GIBBS ENERGY-BASED, ELASTO-VISCOUS MODEL INFORMED BY A COMPREHENSIVE EXPERIMENTAL CAMPAIGN COMPRISING COMPRESSION, VISCOSITY, AND EXTRUSION TESTS

Robert Plachy[1], Stefan Scheiner[1], Florian Arthofer[2], Armin Holzner[2] and Christian Hellmich[1]*

[1]TU Wien

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ABSTRACT

In this contribution, factors are studied which are effective in terms of influencing the die swell of unvulcanized rubber upon extrusion. For that purpose, compression, viscosity, and extrusion tests were performed on two types of ethylene-propylene-diene rubbers, while additional compression tests were performed on natural rubber. Separate assessment of the mentioned testing modalities showed that the compressibility is pressure-dependent; the viscosity is velocity-dependent; and the die swell is influenced by several, partly intertwined factors. Next, dimensional analysis was employed, in order to better understand the significance of the collected experimental data. This way, it turned that the compressibility of unvulcanized rubber is of great importance for the die swell. Surprisingly, the temperature dependence of the die swell was shown to be much less prominent than standardly assumed. Further key factors influencing the die swell involve the geometries of the die and of the extrusion canal.

The described experimental data was furthermore the basis for the development of a novel computational modeling strategy, aiming at prediction of the die swell. To that end, we hypothesize that describing the constitutive behavior of rubber under the premise that rubber is actually a compressible material is key. Hence, we formulate a new mathematical framework considering objective, Gibbs energy-based, and mass-related thermodynamics, using hypo-viscoelastic constitutive material laws. This way, a new set of governing equations was derived, involving only two material parameters, namely the bulk modulus and the viscosity of rubber. In order to solve these equations, we pursue a two-fold strategy. On the one hand, principle of virtual power-based Finite Element scheme was developed, allowing for computing the progress of rubber extrusion over time, and eventually of the arising die swell. Focusing in this paper on circular extrusion dies, due to which the mathematical framework can be formulated and numerically evaluated for the (simplifying) case of rotational symmetry, a set of benchmark simulation was performed. While the results of these simulations corroborate the soundness of the proposed new modeling approach, the numerical implementation is computationally expensive. Hence, as alternative to the numerical solution scheme, we have developed an additional analytical scheme, applicable to conical, circular die geometries, striving for verification of the numerical method. Importantly, taking the compressibility of rubber into account was clearly confirmed to substantially influence the die swell of rubber.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF LOW-CARBON HYBRID MESH STRUCTURES USING MIXED-INTEGER PROGRAMMING

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ABSTRACT

Topology optimization provides a method to design efficient structures that minimize some objective function while respecting certain constraints. The ground structure approach to topology optimization is typically used for truss design. It accomplishes this by filling a design space with numerous candidate truss members and assigning a cross-sectional area to each one. The ground structure approach is beneficial for optimizing large-scale structures because it takes fewer elements to summarize a big space. However, this methodology can generate designs that require many members with unique areas. Fabricating multiple unique members can be difficult and carbon-intensive compared to traditional mass production techniques. Additionally, a design where each member is unique requires contractors to pay great attention to detail during construction.

These issues can be resolved by formulating the ground structure approach as a mixed-integer linear program. Previous work has shown that the mixed-integer formulation allows users to specify manufacturability constraints such as limiting the number of members protruding from a node and the angle of separation between members. Mixed-integer formulations have historically been avoided because of their computational complexity. However, with recent advancements in solvers like GUROBI, mixed-integer problems are more feasible to solve than ever before. This work expands the field of mixed-integer topology optimization by incorporating the mechanics of additional elements, such as plates and shells, into the traditional truss ground structure. Because the algorithm has a larger element library, this work can be applied to a broader range of structures and achieve greater optimality under certain loading conditions. Problem statements are formulated with objectives and constraints that are inspired by several industry standards. The algorithm is tested on benchmark problems and shown to maintain reasonable runtimes with the addition of many new elements through a column generation procedure.

PROPER GENERALIZED DECOMPOSITION FOR TOPOLOGY OPTIMIZATION OF PROBLEMS WITH SEPARABLE GEOMETRY FOR MINIMAL ELASTIC OR THERMAL COMPLIANCE

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ABSTRACT

Many applications of density-based topology optimization require a very fine mesh resolution, either to obtain high-resolution designs, or to resolve physics in sufficient detail. Solving the discretized state and adjoint Partial Differential Equations (PDEs) in every iteration step becomes computationally demanding, restricting the applicability of the method. Model Order Reduction (MOR) offers a solution for this computational burden, using a reduced vector basis for simulations and resulting in a higher computational speed and reduced storage requirements. In scenarios where the multi-coordinate density field can be expressed as a sum of products of lower-coordinate basis functions, one potential MOR technique is Proper Generalized Decomposition (PGD). PGD computes the basis functions on-the-fly as the problem is solved, making it an a priori method. It does not require prior knowledge of the solutions, omitting the need for full system solves, unlike a posteriori methods as Proper Orthogonal Decomposition. Over the last few years, PGD has been successfully used for the solution of various types of PDEs, but it has not yet been applied for topology optimization.

To explore the potential of the method in the context of topology optimization, we use PGD for the optimization of a 3D ribbed floor for minimum elastic compliance and for the optimization of a heat sink device for minimum thermal compliance. The geometry of the models can be expressed as a sum of products of 2D functions for the in-plane coordinates (representing the rib pattern), and 1D functions for the thickness coordinate (representing the distinction between the slab and ribs). The separated PGD approximation is obtained with a method similar to the subspace iterations used for eigenproblems. Numerical tests show significant increase of computational efficiency. To further refine the method, we explore various improvements. The first involves recycling information from prior iterations as an initial guess for the PGD approximation algorithm. Additionally, we investigate a ‘one-shot’ approach, where the approximation is obtained with only one PGD iteration for every optimization step. For both the ribbed floor and the heat sink, numerical tests yield a decrease in calculation time ranging from 100 to 500 times compared to the full approach. Our findings showcase the potential of PGD as a powerful tool in topology optimization of problems with separable geometry, offering substantial gains in computational efficiency without compromising solution accuracy.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ENHANCED REPRODUCING KERNEL SMOOTH CONTACT ALGORITHM

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ABSTRACT

Reproducing kernel (RK) smooth contact [1] is a node-to-surface contact algorithm which constructs a smooth master surface by interpolating the surface node locations using the RK approximation. This leads to greater accuracy and stability in the contact force and contact surface approximation compared to finite element-based formulations since the latter must discard higher-order derivative terms. However, if the dimension of the master surface is comparable to the slave body's nodal spacing and the master-slave relationship cannot be reversed due to topological changes, sporadic (or possibly no) contact will be detected. Furthermore, attempting to solve this problem by local refinement assumes one knows the contact surface a priori, while a global refinement solution vastly increases the number of DOFs and decreases the critical timestep. We present two modifications to RK smooth contact as a viable solution to this problem. First, we improve the contact detection by utilizing spherical representations of the slave nodes, a tactic with some similarities to the pinball algorithm [2]. Second, because the first modification likely overestimates the slave body's contact surface area, we introduce an indentation energy-based, gap-dependent penalty formulation for impenetration constraints. These two modifications improve contact detection for coarse slave discretizations while reducing the effect of mesh-dependency. We demonstrate the effectiveness of our formulation with several examples.

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Key Words: Reproducing Kernel Particle Method, Meshfree Methods, Smooth Contact, Energy-Based Contact Algorithm, Multi-Body Contact

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SHAPE CHANGING METAMATERIAL

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ABSTRACT

Metamaterials are materials engineered at the nano or micro scale with repeating unit structures designed to exhibit properties that are not available with other materials. The unit structure is carefully arranged to create unique electromagnetic, acoustic, thermal, or mechanical behaviors. Smart metamaterials or adaptive metamaterials are a special category of metamaterials that can dynamically alter their properties in real time due to external stimuli or changes in the environment. Adaptability is achieved through incorporating active elements in the metamaterial microstructure. Smart metamaterials, while promising, have been limited in their response properties primarily due to low strain values. To overcome this restriction, a unique metamaterial has been developed that is capable of large strain outputs. Additionally, Kirigami-like openings (cuts) are introduced at the element level and at larger scales to increase the flexibility and capabilities of the material. Morphing macro structures are built from this smart metamaterial that are capable of large-scale deformation such as flapping, folding-unfolding and soft robotic motion or manipulation.

DATA-DRIVEN DISCOVERY OF GOVERNING EQUATIONS AND MECHANICAL PROPERTIES FROM EXPERIMENTAL ULTRASONIC DATA WITH QUANTIFIED UNCERTAINTY

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ABSTRACT

This study presents an example of learning governing equations, with quantified uncertainty, in a data-driven framework from experimental mechanics data sets. Here we apply the weak form of the Sparse Identification on Nonlinear Dynamics (WSINDy) for partial differential equations (PDEs) [1] to learn governing equations from experimental data sets. Specifically, we use our modified version of the WSINDy for PDEs algorithm which implements ensembling as a method for quantifying the uncertainty on the model terms and coefficients.

The experimental data sets considered here come from laser ultrasonics tests conducted on two materials, aluminum and a granular composite of IDOX crystals and an Estane binder. We have previously shown that for long wavelength experimental inputs, the WSINDy for PDEs algorithm recovers Euler-Bernoulli beam models for both materials at the macroscale [2]. Applying the ensemble version of the WSINDy algorithm to this same data, we discover the same beam model form and recover uncertainty information for the terms in the model and the corresponding coefficients. Moreover, from the discovered PDEs we can recover the Young's modulus for both materials with uncertainties. For aluminum, our recovered Young's modulus values are within 4% of the nominal Young's modulus for aluminum of 69 GPa and have a standard deviation of 0.55 GPa. With the IDOX/Estane data, the mean recovered Young's modulus is 0.911 GPa with a standard deviation of 0.0069 GPa, which is consistent with values from previous studies which used different experimental methods. This work provides an example of how data-driven equation discovery methods can be used with experimental data sets to simultaneously learn governing equations and mechanical properties with quantified uncertainty for mechanics applications.

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Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FINITE ELEMENT MODEL UPDATING OF MITER GATES WITH NONLINEAR BOUNDARY CONDITIONS USING STATIC STRAIN MEASUREMENTS

Trent Schreiber[1] and Yang Wang[1]*

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ABSTRACT

Navigation locks are a significant piece of the inland waterway infrastructure in the United States. Due to deterioration and barge impacts, gaps develop between the surfaces supporting the lock gates. These gaps in the boundary conditions create a redistribution of stress that is typically not accounted for in design, which can lead to accelerated deterioration and possibly unexpected failure of the gate. This research presents a novel approach to detecting gaps in the boundary conditions of miter gates, a common type of lock gate. The approach in this paper is to model the gaps as nonlinear springs. The unknown spring parameters are estimated using an optimization problem that minimizes the difference between in-situ measured strain and the strain simulated by the finite element model. The problem is nonconvex, therefore, multiple local searches are performed to increase the chance of finding the global optimum. Two types of nonlinear springs are considered, namely, a gap element and a cubic spring. The formulation of the model updating problem is presented followed by validation with numerical examples. It is shown that both types of springs provide sufficient accuracy, but the cubic spring has a much lower computational cost.

A MACHINE LEARNING APPROACH FOR HURRICANE-INDUCED FLOOD DEPTH ESTIMATION: A CASE STUDY ON HURRICANE HARVEY

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ABSTRACT

Urban flooding, resulting from the combined effect of extreme precipitation and storm surge, is a growing threat to coastal cities. It requires reliable and efficient modelling tools for risk mitigation and emergency response. In this context, recent advancements in machine learning (ML) techniques have opened new avenues for enhanced flood hazard assessment in such complex scenarios, characterized by a non-linear interplay of several diverse factors influencing inundation characteristics.

This study leverages Hurricane Harvey as an emblematic case study of compound flooding in coastal regions. In August 2017, the Houston Metro region experienced an unprecedented amount of rainfall, with accumulations of 900-1200 mm over a 5-day period, coupled with a storm surge ranging from 0.8 to 1.3 m. These extreme conditions led to catastrophic flooding across numerous areas in Harris and Galveston counties (Blake & Zelinsky, 2018).

The abundance of observed data from this event facilitates the investigation on the application of ML approaches for predicting water depths and analyzing the relative importance of the various factors governing inundation phenomena in hurricane-induced flooding. In detail, we sampled flood depth in 5,000 locations from the FEMA dataset compiled for Harvey damage assessment (FEMA, 2023). To capture the potential factors influencing flooding mechanisms, we enriched the dataset with information on the built and natural environment, as well as morphological and land-use features sourced from open-data and processed in a GIS framework. Hazard-related data, including storm surge and rivers' stages, were also incorporated as explanatory variables.

The methodology involved the application of Extra Trees and Random Forests algorithms to the elaborated dataset, using different combinations of the predictive features as input. The accuracy of the developed ML models in predicting flood depths was benchmarked against previous studies that employed traditional physically-based models for the same case study.

Our findings demonstrate satisfactory accuracy, reporting similar or even surpassing benchmark prediction errors in the literature, and also yield valuable insights into the major physical drivers influencing flooding during hurricanes. Furthermore, this study highlights the practical benefits of these advancements in flood risk management, suggesting the potential integration of ML predictions into real-time flood monitoring systems and enhanced early warning mechanisms.

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Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CALIBRATION OF HYBRID CONSTITUTIVE MODELS FROM FULL-FIELD DATA

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ABSTRACT

Constitutive models play a vital role in computational simulations, where they serve as closure relations for the general conservation laws of physics. Calibration is the process of estimating the parameters in a constitutive model from experimental characterization data. Generally, experiments provide indirect measurements of a material's response (e.g. applied force vs extension), which can only be directly related to constitutive model outputs in special circumstances (e.g. uniaxial stress in a tensile test prior to necking). In recent years there have been efforts to combine conventional constitutive models with machine learning (ML) components to produce hybrid constitutive models with the promise of increasing predictive accuracy and/or providing flexibility in the calibration process.

However, the scientific ML research community overwhelmingly favors training data in the form of direct constitutive model responses (e.g. stress-strain data from another model). This focus on direct measurements is stifling progress by divorcing ML models from their ultimate application within large-scale physics simulations and preventing the use of sources of experimental data that provide indirect measurements. These include infrared thermography and digital image correlation, information-rich metrology techniques for obtaining full-field temperature and deformation (i.e. displacement and strain) measurements, respectively, on the surface of a test specimen.

Furthermore, conventional constitutive models extrapolate in a manner that is well-understood and inherently stable. On the other hand, off-the-self ML models can extrapolate in undesirable, sometimes catastrophic ways. Robust extrapolation is crucial for constitutive models because characterization tests are limited by the design of laboratory equipment — they cannot impose arbitrary states of mechanical and/or thermal loading onto a material. Hence, in an application simulation, a constitutive model will surely extrapolate from the available data.

In this talk, we will discuss the structure of our hybrid models, training methods, and results obtained using synthetic and experimental full-field datasets.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHALLENGES IN HYDRO-REAL-TIME HYBRID SIMULATION TO EXAMINE THE RESPONSE OF FLOATING OFFSHORE WIND TURBINES

Akiri Seki[1], Yun Ni[1], Bret Bosma[2], Barbara Simpson[1], Bryson Robertson[2], Ted Brekken[2], Andreas Schellenberg[3] and Pedro Lomonaco[2]*

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ABSTRACT

The energy transition from fossil fuels to renewable energy is crucial to promote sustainable development. Seeing wind energy provided 10% of U.S. total utility-energy in 2022, offshore wind turbines (OWTs), which can access large wind resources offshore, have huge potential to contribute to the energy transition. Floating OWTs is a financially feasible option where water depth increases sharply near the coast but is subjected to complex dynamics by wave and wind. However, data of realistic fluid-structure interaction response is very limited due to: [i] limitations in experimental techniques that necessitate geometrically scaled structures along with similitude of the forces and time for the waves and wind, and [ii] computationally expensive cost and uncertain accuracy of numerical results in handling combined computational fluid and structural dynamics. Real-time hybrid simulation (RTHS) is a testing method that divides a system into numerical and physical sub-assemblies interacting, in real time, through sensors and actuators. RTHS can alleviate the aforementioned constraints by scaling, force, length and time between the sub-assemblies. This study discusses the application of RTHS using a three-loop hardware architecture to simulate response of the 5MW floating offshore wind turbine developed by NREL. Discussion includes modification made in OpenFAST to be used in the three-loop hardware architecture, time synchronization over the three individual machines composing the system architecture. Challenges in force control in 6DOF will be discussed by the second author.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF DIFFERENT TORNADO CHAMBERS ON VORTEX STRUCTURE AND VORTEX PARAMETERS

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ABSTRACT

Every year extensive damage happens due to tornadoes. To mitigate this damage, several different vortex chambers are built to understand the tornado force on building. Verma and Selvam (2021) classified the existing vortex chambers as (1) Side opening system (SOS) (2) Top full opening system (TFOS) and (3) Top partial opening system (TPOS). Only a few preliminary works are reported on the vortex formation and vortex parameters in the existing work. They changed the aspect ratio from 1 to 0.5 for the SOS. The CFD model based on staggered grid reported in Verma and Selvam (2020 & 2021) was validated with VoTECH chamber measurements from Texas Tech University. The vortex parameters used by Verma and Selvam to validate their model are maximum tangential velocity (Vtmax), radius of the core (rc), vertical height of the location of rc (zc) and touchdown swirl ratio (STD).

Still the understanding of the mechanism of touchdown with different chambers are not clear and their effect on vortex parameters are also not available. This understanding helps to design efficient vortex chambers in the future. The models based on non-staggered grid had spurious pressures and also over predicts STD. Some of the results using openFoam will be reported in this regard. The CFD model based on staggered grid will be used for further study to understand the process by which touchdown happens as well as other vortex parameters for comparison. The research findings will be reported with proper visualization.

Since CFD modeling takes extensive computer time when the aspect ratio (ho/ro) is smaller, the inhouse CFD code is improved by hybrid methods like FDM for solving momentum equations and cosine transform fast solver for pressure solution. The performance and details of the computation will be reported.

BRIDGE MODAL IDENTIFICATION USING TIME-FREQUENCY ANALYSIS OF MOBILE SENSING DATA

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ABSTRACT

Mobile sensing has emerged as an efficient solution for large-scale bridge monitoring compared to traditional stationary sensor networks. In conjunction with crowdsourcing, smartphone acceleration and GPS data collected inside cars traversing the bridge can be used to estimate the dynamic properties at low cost. However, there are inherent difficulties in leveraging the vast dataset for this purpose. The data is highly contaminated by the effects of unknown vehicle dynamics and additional vibrations introduced by the road profile. This work focuses on developing algorithms that are robust to these effects. Previous works include estimating natural frequencies and absolute mode shapes on multiple real-world case studies, utilizing data from actual ride-sourcing data streams, such as Uber. This current work expands on this with the development of an algorithm that takes in this mobile data to estimate a cross-spectrum synonymous with a fixed sensor analysis. Furthermore, the method works on the same principles of spatially averaging frequency contents of mobile sensor trips, which led to the success of previous methods.

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCEMENT LEARNING-BASED POST DISASTER RESOURCE ALLOCATION FOR ENHANCED INFRASTRUCTURE RESILIENCE

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ABSTRACT

Natural disasters such as extreme seismic events and climate change related events such as floods and hurricanes have been on the rise in the recent past. This necessitates the enhancement of resilience of communities to such natural disasters. This can be achieved through better design, continuous monitoring, and efficient and swift post-disaster recovery. In this work, we focus on efficient recovery strategies subject to limited financial and human resources available for such activities. Typically this is treated as a high-dimensional multi-objective optimization problem that generally is limited by computational inefficiencies. Instead, we formulate this task as a sequential decision-making problem and use deep reinforcement learning to develop optimal resource allocation strategies for network systems consisting of interdependent infrastructure. We demonstrate the efficacy of the proposed framework using a virtual test-bed and simulated disaster scenarios.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MESOSCALE COMPUTATIONAL MODELING ON SQUARE-SHAPED GRANULAR SALT UNDER WEAK SHOCK COMPACTION

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[1]Los Alamos National Laboratory

ABSTRACT

The mechanical response of granular salt under a wide range of tectonic rates of loading is of great interest for ensuring the structural reliability of a salt dome, which serves as underground storage for oil and natural gas and as containment for radioactive waste disposal. Despite the presence of deformable granular matter in various engineering and defense applications, there is a limited understanding of its mechanical response under moderate-rate loading scenarios. This study addresses this gap by investigating the mesoscale response of granular salt under weak shock compaction through integrated experimental methods and computational modeling. A linear shock compaction experiment was performed on table salt, accompanied by optical imaging to characterize the shock velocity. To understand the particle-scale response, mesoscale simulations were performed using the FLAG hydrocode utilizing square-shaped grains under loading and boundary conditions identical to experiments. The simulated results indicate the appearance of force chains and the heterogeneous nature of the shock wavefront, with their levels influenced by the impact velocity. Furthermore, force chains display a preferred path based on the contact types of square-shaped grains. By gaining insights into the dynamic response of granular salt under weak shock, this study provides insights into the mechanics of granular salt within a geotechnical context.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RELIABILITY-BASED OPTIMIZATION OF REGIONAL BUILDING RETROFIT STRATEGY USING BUFFERED FAILURE PROBABILITY

Uichan Seok[1], Ji-Eun Byun[2] and Junho Song[1]*

[1]Seoul National University
[2]University of Glasgow

ABSTRACT

Growing concerns over climate change and the increase in natural disasters highlight the urgent need to enhance urban infrastructure resilience at a regional level. This study focuses on building structures as essential social and economic assets, advocating cost-efficient retrofitting as an essential strategy for risk mitigation. This approach involves quantifying uncertainties impacting disasters through local-level risk assessments and evaluating the performance of models incorporating these uncertainties. Decision-making processes benefit from these assessments, balancing between cost and risk reduction. The proposed framework utilizes Performance-Based Engineering (PBE) and Reliability-Based Optimization (RBO). PBE, evolving from its origins in seismic engineering, has become a versatile methodology applicable to various disasters, including tsunamis and tornadoes. From the perspective of RBO, a reliability metric known as buffered failure probability is employed. Unlike conventional failure probability, this metric offers insights into the risk accounting for the severity of failures and is compatible with sampling-based PBE results, ensuring computational efficiency. The formulation of limit state functions considers total regional loss, translating it into a mixed integer linear optimization problem that captures the binary nature of retrofitting. The study also introduces a modified active-set strategy using buffered failure probability, effectively tailored for building retrofit challenges. A demonstration of the proposed methodology with a testbed of 1,000 buildings in Seaside, Oregon, showcases its applicability to optimal decision-making under compound disaster scenarios involving earthquakes and tsunamis. The proposed approach is also extended to examine critical factors influencing these decisions to provide comprehensive insights.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIBRATION ATTENUATION IN A MASS IN MASS FRICTIONAL METAMATERIAL UNIT CELL: AN ANALYTICAL INVESTIGATION

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ABSTRACT

The paper presents a mass in mass frictional metamaterial unit cell for vibration attenuation study. The structure of the unit cell contains a hollow outer mass (externally excited) with a spring-damper connected inner mass, with friction acting at the interface of the two masses. Coulomb's friction law is employed to model the frictional interface. The dynamic equations of motion are discretized using Euler's discretization scheme. The non-linearity of the frictional force is simplified using a linear complementarity problem (LCP) based approach and a time domain solver is formed to study the dynamics of frictional systems. The transmission spectrum of the aforesaid unit cell is studied and it can be observed that the unit cell has a wide low frequency attenuation band gap for medium range of frictional force at the interface between the two masses. The energy dissipation due to friction enables the unit cell to qualify to be used for vibration control. Further, the metamaterial unit cell is then used as a building block of a metamaterial chain and the vibration attenuation can also be observed in the transmittance spectrum of the metamaterial chain.

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Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT AND CHALLENGES IN IMPLEMENTING A PHYSICS-INFORMED NEURAL NETWORK FOR PREDICTING GROUND-PENETRATING RADAR DATA

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ABSTRACT

The research focuses on the innovative integration of Physics-Informed Neural Networks (PINNs) into the realm of Ground-Penetrating Radar (GPR) data prediction, a pioneering step in geophysical exploration. This paper presents a comprehensive development framework for a specialized PINN model that is adept at interpreting and forecasting GPR data, harnessing the synergy between deep learning algorithms and physical laws governing subsurface structures. The core of this study lies in embedding the physics of electromagnetic wave propagation into the neural network, ensuring that the model's predictions adhere to fundamental physical principles.

However, this integration poses several notable challenges. First, the complexity of accurately modeling subsurface heterogeneities and boundary conditions in a neural network is addressed, with an emphasis on the need for robust training datasets that adequately represent diverse geological scenarios. Secondly, the computational intensity of training such specialized networks, particularly in the context of large-scale GPR datasets, is examined. Strategies to optimize computational efficiency without compromising the accuracy of predictions are explored.

The paper also delves into the challenge of generalizing the model to handle various soil types and moisture levels, crucial for the wide applicability of the technology in different geological settings. Techniques for enhancing the model's adaptability and resilience against noisy and incomplete data, common in real-world GPR applications, are presented.

In conclusion, this paper not only contributes a novel approach to GPR data analysis but also opens avenues for future research in the fusion of machine learning and geophysical methods. The development and optimization of the proposed PINN model pave the way for more accurate, efficient, and versatile geophysical explorations.

SYNTHESIS OF A LUMINESCENT TRACER FOR CRUDE OIL USING A MULTIBAND RED/NIR/SWIR MGALGEO3:PR3+ PERSISTENT PHOSPHOR MATERIAL

Syed Niaz Ali Shah[1], Yafei Chen[1] and Sikandar Khan[1]*

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ABSTRACT

Persistent luminescence, commonly referred to as afterglow, is the prolonged emission of light by a material after the cessation of excitation, lasting from minutes to hours. There has been significant research on persistent phosphors that emit in the visible spectral range, leading to several commercially successful materials widely employed in night-vision applications across various fields. Over the past few years, there has been a growing interest in persistent luminescence extending beyond the visible spectral region, specifically in the near-infrared (NIR; 700-900 nm) and short-wave infrared (SWIR; 900-1700 nm) spectral domains. This increased attention is due to the numerous promising applications associated with longer-wavelength persistent luminescence, spanning from infrared night-vision surveillance to advancements in biomedical imaging. In this study, we employed the sol-gel process to synthesize multiband MgAlGO3:Pr3+ persistent nanoparticles (NPs) capable of emitting in the visible, near-infrared (NIR), and short-wave infrared (SWIR) wavelength ranges. Our investigation revealed that the introduction of Al3+ ions significantly enhances both the afterglow intensity of MgGeO3:Pr3+ phosphor and the afterglow decay time of Pr3+ emission. These synthesized materials were utilized under background fluorescence-free conditions for ultrahigh-sensitive detection in crude oil. The MgAlGO3:Pr3+ NPs are capable of being re-excited within the emulsion, allowing for repeated spectral and imaging acquisitions. The high sensitivity not only enables precise imaging of the NPs in crude oil but also facilitates long-term monitoring in real time. Furthermore, the MgGeO3:Pr3+ phosphor is expected to find intriguing applications in biological imaging, night-vision surveillance, and photovoltaics.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND-INDUCED VIBRATION OF HIGH MAST ILLUMINATION POLES – FIELD MONITORING AND MITIGATION

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ABSTRACT

High mast illumination poles (HMIPs) are tall and slender structures typically installed on interstate highways to provide high-level illumination. These structures consist of a light assembly and a lowering device mounted on a flexible tubular cantilever, typically ranging from 80 to 150 feet in height. Although HMIPs have a simple design that complies with the code, they are known to have low inherent damping and, hence are susceptible to wind-induced vibrations. Several cases of premature fatigue cracks were discovered on newly installed HMIPs in Kansas. Video recordings revealed that the light poles experienced cyclic displacements with large amplitudes, which can cause fatigue cracking due to high-stress demand at the bottom. To reveal the underlying mechanism of wind-induced vibrations of these structures, a 100 ft-tall HMIP with three LED luminaires located in Wakeeney, Kansas, was instrumented with wireless sensors for long-term monitoring. The field data revealed wind buffeting as the leading cause of excessive vibrations for the monitored HMIP, while vortex-induced vibration occurred at much lower amplitudes. In light of the findings from field monitoring, this study proposed a novel design of a constrained layer damper (CLD) for mitigating buffeting-induced vibrations. Conventional CLD uses a single constraining layer wrapped over the viscoelastic layer, which becomes ineffective when applied on tubular structures due to the overlapping neutral axes between the base structure and the constraining layer. Therefore, we proposed a new design of CLD that incorporates multiple longitudinal slits in the constraining layer to separate the neutral axis of the base structure from the constraining layer. Such a separation allows the viscoelastic layer to develop shear strain when the structure undergoes bending deformation. A comprehensive numerical simulation was carried out to examine the impact of different design parameters, such as the thicknesses of the viscoelastic material and the constraining layer, on the level of damping enhancement for tubular structures. The results showed that the proposed CLD could double the damping level of the HMIP and reduce its steady-state response at the first-mode resonance by 57%.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A THREE-DIMENSIONAL ANISOTROPIC LOCALIZING GRADIENT DAMAGE MODEL FOR TRANSVERSE ISOTROPIC MATERIALS: WITH EMPHASIS ON TIMBER

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ABSTRACT

We present a new damage model for transversely isotropic materials, with a special focus on timber. The model proposed in this study is formulated by employing the localized gradient form of continuum damage theory. The model accounts for anisotropic damage through two damage variables, delineating damage parallel and perpendicular to the grain, representing isotropic damage within the cross-sectional plane. An additional fourth-order tensor transformation is incorporated to facilitate the conversion between the global and local reference frames, allowing for arbitrary spatial orientations of the material matrix. We specifically concentrate on damage arising from tensile and shear stresses, with no exploration into the ductile damage of timber caused by compressive stresses. While our model has the potential for extension to three different damage variables (two within the cross-sectional plane) by introducing a third Finite Element sample, it is important to note that, in the interest of maintaining a low computational cost, these extensions are not explored within the scope of this paper.

The performance verification of the model relies on numerous numerical examples, incorporating experimental benchmark problems. The outcomes demonstrate that the suggested damage model adeptly captures both the initiation of failure and the propagation of damage.

ASSESSMENT OF PARTICLE DAMPING SYSTEMS IN REDUCING MOTION OF FLOATING WIND TURBINE PLATFORMS

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ABSTRACT

Floating wind turbines are considered essential for expanding electricity generation from wind resources due to the water depths limitation of monopile wind turbines. The major impediment is the wave-induced loads that induce significant oscillations, which in turn causes potential reduction in the energy generation and potentially compromise their structural integrity leading to their failure. This paper explores the application of particle damping systems as an effective method to mitigate vibrations of floating wind turbine platforms. Particle damping is a passive vibration control technique that utilizes loose spherical particles within a confined space to dissipate vibrational energy. By analyzing the dynamic behavior of floating wind turbines and the application of particle damping, this study presents a comprehensive assessment of the effectiveness of this damping system in reducing platform vibrations. The research approach involves experimental tests to compare the floating platform's performance with and without the particle damping system by evaluating its impact on platform motion reduction and tension reduction in the mooring lines. The experiments were carried out in the wave tank of the Davidson Laboratory at Stevens Institute of Technology. The findings highlight the potential of particle damping to enhance the structural integrity and performance of floating wind turbines, contributing to the advancement of offshore renewable energy technologies.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SPHEROIDAL HARMONICS (SOH) FOR GENERALIZING THE ANALYSIS, RECONSTRUCTION, AND GENERATION OF GRANULAR MATERIALS

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ABSTRACT

The granular mechanics community extensively uses the spherical harmonics (SH) approach for characterizing the morphology of particulate matter [1]. The radial-based SH approach is applied to star-shaped particles by radially mapping vertices onto a unit sphere and then projecting the spatial data on the spherical basis functions. SH was used to generate statistically realistic random particles, with a given fractal dimension, to generate virtual microstructures that assist as input geometries in discrete and finite element simulations. The radial-based SH is powerful and computationally cheap, especially when hundreds of particles are involved.

The SH-based reconstruction approach can often result in oscillatory noise particles that are prolate or oblate in shape (low true sphericity index). The oscillations in the reconstruction occur from expanding the data onto a unit sphere with a highly nonuniform distribution of points. The large gaps among the vertices onto the unit sphere can band-limit the analysis, where the expansion diverges for higher frequencies. To eliminate these high-frequency oscillations, we proposed the spheroidal harmonics (SOH) approach to reduce the gaps between the vertices onto the corresponding spheroidal domain. We choose the spheroidal harmonics basis as spheroids geometrically generalize the spheres and they are mathematically close to the spherical harmonics basis. In addition, the spheroids are generally used to classify granular particles in laboratory tests. Here, we present two SOH-based approaches: (i) radial-based SOH for star-shaped (SS) particles and (ii) conformal-based SOH for non-star-shaped (NSS) particles.

For the SS particles, we start by classifying the particles and finding the proper spheroidal (oblate or prolate) domain. Then, we find the corresponding harmonic functions for that spheroid before proceeding to the standard analysis and projection step. The second approach for NSS particles depends on finding an angle-preserving diffeomorphism that is an SS image of the input surface. This is done by smoothing the surface with multiple angle-preserving cycles (conformal mapping). After that, we use the preprocessed input to analyze the surface of the stone as proposed by the first radial-based approach. The results of both SOH approaches surpass the reconstruction quality of the traditional SH. This should enhance the quality of characterizing and modeling granular surfaces. The proposed approaches generalize the traditional SH without drastically changing the existing pipelines and codes for analysis and generation.

[1] - Zhao J, Zhao S, Luding S. The role of particle shape in computational modelling of granular matter. Nature Reviews Physics 2023;5(9):505–25. DOI:10.1038/s42254-023-00617-9.

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SUBSIDY FOR REPAIR IN COMPONENT MAINTENANCE GAMES

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ABSTRACT

Maintenance of critical infrastructure, as like transportation and energy networks, typically involves joint responsibility shared among multiple stakeholders who own individual pieces of the large system, and failure of coordination can lead to disastrous consequences. We consider a game theoretic formulation of the infrastructure maintenance problem where the system consists of several components owned by different agents, and study the problem of subsidy design to lead the agents to better equilibria. Agents maintain binary components, where each component is either intact or damaged according to some prior probability, and the overall system either functions or fails based on the states of the individual components. The agents are responsible for the repair costs of their own components, and the penalty for system failure is experienced by all the agents. The game was introduced by Lin, Balcan, Blum and Pozzi (2021), who illustrated the possibility of rational agents ignoring freely available information about the component's true state for selfish reasons and in turn increasing the overall expected cost for the system. In this work, we propose a general subsidy design approach for reducing the social cost in the component maintenance game. We show that the ratio of the social cost in the worst case equilibrium to the optimal social cost (the Price of Anarchy) can be very large, especially when there is a large number of components in the system. In contrast, we show that via subsidy a central agent can improve the system performance, where the subsidy may be obtained via taxes collected from the agents. While good values of subsidy are easy to compute in simpler two-agent games, it is computationally hard to do so for general n-agent games under standard complexity theoretic assumptions. We show that this is the case for designing subsidy allocation for three distinct goals for the central agent -- minimizing the total cost in the worst-case equilibrium, guaranteeing that the system functions in any equilibrium and tackling the undesirable information avoidance behavior of the agents. On the positive side, we show that we can learn provably good values of subsidy in repeated games coming from the same domain. This data-driven subsidy design approach avoids solving computationally hard problems for unseen games by learning over polynomially many games. We also show that in addition to reducing the social cost, providing subsidy can be useful in avoiding undesirable information avoidance behavior when the maintained components are inspected.

Advances in vibration and structural control

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEISMIC ISOLATION OF STRUCTURE USING GEOFOAM INSERTS IN SOIL

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ABSTRACT

As seismic events continue to pose significant challenges to infrastructure worldwide, the pursuit of viable and sustainable methods to reduce damage caused by earthquakes remains of utmost importance. In this paper, we explore the potential application of geofoam inserts to shield structures from seismic waves. Using transfer matrix formulation advanced by W. T. Thomson, we investigate the attenuation of both vertically propagating and inclined seismic waves in soil with geofoam inserts. Different optimization techniques were adopted to estimate the optimum number and placement of geofoam inserts, and to tune the properties of the geofoam layer to efficiently attenuate elastic waves in the 1 to 10 Hz frequency range. Findings from this study contributes to the understanding of seismic wave propagation through layered media and offers deeper insights into the design parameters essential for effective seismic isolation of structure in this frequency band.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BENDING PERFORMANCE OF 3D STEEL AUXETIC LATTICE REINFORCED CONCRETE

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ABSTRACT

In recent years, lattice reinforcements to concrete have gained significant attention for their remarkable strength and ductility enhancement. Concrete being weak in tension and strong in compression, has motivated the exploration of reinforcement techniques such as conventional, fibre, and lattice reinforcements. While much of the existing research predominantly focuses on polymer-based lattice reinforcements, this study takes a novel approach by investigating the potential of 3D steel auxetic lattices. Auxetic lattice with a negative Poisson ratio (NPR) utilizes auxeticity as an active confinement technique to concrete which in response increases the strength and ductility of concrete members. This research presents the bending performance of 3D steel auxetic lattice-reinforced and conventionally reinforced concrete beams. To assess the bending behavior of beams reinforced with auxetic reinforcement, we employed a four-point bending test. The re-entrant angle of the auxetic reinforcement was systematically varied along the depth of the beam, transitioning from the tension zone to the compression zone. The results underscore a notable enhancement in the peak strength and ductile behavior of beams reinforced with auxetic lattice compared to conventionally reinforced concrete beams. The study shows the potential of auxetic lattice reinforcements to enhance resilience and performance under extreme loading conditions, such as earthquake.

A new horizon - Quantum computing and quantum materials (by invitation only)
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS OF SUPERCONDUCTIVITY—BEYOND THE CLASSICAL GINZBURG-LANDAU THEORY

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ABSTRACT

Superconductivity is a phase of matter where electrons pair up due to a strong correlation to create `Cooper pairs' that move without resistance from the atoms. The celebrated Ginzburg-Landau theory of superconductivity describes a phase transition from a non-superconducting to a superconducting phase around a critical temperature. We re-examine the classical Ginzburg-Landau theory of superconductivity in light of a suggestion made by Gurtin, incorporate the effect of mechanical deformation and provide fresh insights into the design of next-generation superconductors.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRONG FORM MESHLESS ANALYSIS OF SOLIDS USING CONSTRAINED POLYNOMIAL DIFFERENTIAL OPERATORS

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ABSTRACT

While computational strategies to solve solid mechanics problems have traditionally focused on the weak form of equilibrium, there has been a renewed interest in solving the strong form. This study proposes a meshless approach to solve the strong form by developing a special class of finite difference operators over arbitrary (non-rectangular) grids. First, this class of operators is derived, and then, these operators are used to formulate an entire numerical solution method for solid mechanics.

The proposed class of finite-difference (FD) differential operators is derived via partially constrained local polynomials. Polynomial interpolation over arbitrary grids in more than one dimensions, despite providing high accuracy it lacks robustness as it often suffers from singularities (and ill-conditioning), which makes it unattractive for generating FD operators. To bypass this challenge, polynomial interpolation is usually replaced by polynomial approximations (as opposed to interpolations) over several points that exceed the number of the polynomial coefficients, resulting in overdetermined systems solved as least-squares approximations. This latter approach, despite enhancing robustness, reduces accuracy. The present study proposes FD differential operators derived via partially constrained local polynomials that enforce interpolation in the vicinity of the reference point and approximation away from the reference point. Such an operator combines high accuracy attained from the local interpolation and robustness attained using several interpolation points that is larger than the number of the polynomial coefficients. For the proposed operator, the support domain is separated into two sub-domains, a short-range sub-domain controlled by interpolation and a long-range sub-domain controlled by approximation. The extent of these sub-domains is automatically generated such that the numerical error of the approximation due to potential ill-conditioning is below a selected tolerance via a proposed algorithm. The proposed FD differential operators are compared with FD differential operators derived via overdetermined polynomial approximations as well as against analytical solutions in terms of accuracy and convergence properties.

Following spatial discretization of the domain into a set of nodes, these operators are generated, and are used to convert the differential equations of equilibrium and the strain-displacement differential equations into a set of algebraic equations over a spatially discretized solid domain. Following application of the displacement/essential BCs and the traction/natural BCs, a system of linear (for elastic material response) or nonlinear (for inelastic material response) algebraic equations is solved to produce the solution. Examples are presented for 2D problems in elasticity and plasticity.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-OBJECTIVE FEEDBACK DESIGN FOR SELF-POWERED STRUCTURAL CONTROL SYSTEMS

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ABSTRACT

A structural control system is called “self-powered” if it can operate solely using the energy extracted from the response of the plant in which it is embedded. Due to dissipative losses in the control transducers, associated power electronics, and the energy storage subsystem, self-powered control laws must adhere to feasibility conditions that are more stringent than classical passivity. In this paper, we present a methodology for the synthesis of feedback laws for self-powered structural control systems, assuming a stochastic disturbance model. We assume a multi-objective mean-square performance measure for the design of the control law, which explicitly balances drifts against accelerations in stationary response. The control design approach consists of two stages. In the first stage, we optimize an linear, time-invariant, colocated feedback law that adheres to the self powered feasibility constraint. In the second stage, we design a nonlinear, full-state feedback controller that is guaranteed to improve upon the closed-loop performance obtained by the first stage design and maintain feasibility. We demonstrate the implementation of the control technique, and the design tradeoffs that arise, in a simulation example.

MESOSCOPIC DISCRETE MODELING OF TENSION STRENGTH REDUCTION OF CONCRETE TENSION STRENGTH DUE TO FINE FIBER CONTENT INCREMENT

Lei Shen[1], Qingwen Ren[1] and Maosen Cao[1]*

[1]*Hohai University*

ABSTRACT

A mesoscopic discrete model for fine PP fiber reinforced concrete (PFRC) is proposed in this work, which is called LDPM-FineF. Tow contributions are presented in LDPM-FineF. First, the LDPM-FineF defines an equivalent coefficient of fiber diameter to gain a balance between the modeling accuracy and computational cost caused by the great number of fine fibers with diameter 100 micro-meter. With this feature, the LDPM-FineF is able to simulate the mechanical behavior of Engineered Cementitious Composites (ECC). Second, the LDPM-FineF is able to predict the unimodal variation of tension strength of PFRC with increasing fiber content. The mechanism behind this phenomenon is explained as the combination of mesoscopic mechanics and fiber ``near-field effect''. The initial addition of PP fiber can increase the matrix strength, so that can slightly increase the PFRC tension strength. The further increase dosage of fine PP fiber keeps reducing the tension strength, since the strength contribution of fiber bridging force is smaller than the replaced matrix.

Machine learning and its applications in civil and mechanical engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS-INFORMED AI MODELS OF ROCKING RESPONSE AND THE ROLE OF GROUND-MOTION CHARACTERISTICS

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ABSTRACT

The seismic response of a wide variety of structures, from small but irreplaceable museum exhibits to large bridge systems, is characterized by rocking. Besides, rocking motion is increasingly being used as a seismic protective strategy to limit the amount of seismic actions (moments) developed at the base of structures. However, rocking is a highly nonlinear phenomenon governed by non-smooth dynamic phases that make its prediction difficult. This study presents an alternative approach to rocking estimation based on a Physics-informed Convolutional Neural Network (PICNN). By training a PICNN framework using limited datasets obtained from numerical simulations and encoding the known physics into the PICNNs, important predictive benefits are obtained relieving difficulties associated with over-fitting and minimizing the requirement for large training database. Two models are created depending on the validation of the deep PICNN: the first model assumes that state variables including rotations and angular velocities are available, while the second model is useful when only acceleration measurements are known. The analysis is initiated by implementing K- means clustering. This is followed by a detailed statistical assessment and a comparative analysis of the response-histories of a rocking block. It is observed that the deep PICNN is capable of effectively estimating the seismic rocking response history when the rigid block does not overturn.

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF INCORPORATING HURRICANE DURATION ON THE REGIONAL LOSS ASSESSMENT OF A PORTFOLIO OF WOODEN STRUCTURES USING SIMULATION-BASED FULL TRACK APPROACH

Chao Sheng[1] and Paolo Bocchini[1]*

[1]Lehigh University

ABSTRACT

The rational and accurate damage and risk assessment for a portfolio of structures and infrastructures in coastal communities subjected to hurricanes is crucial for disaster preparedness, risk management and mitigation, and insurance premium pricing. The currently adopted methodology primarily relies on the use of the catastrophe modeling framework, consisting of, in general, hazards, exposure, vulnerability, and loss models. To estimate hurricane risk, there exist two types of analysis procedures. First, the maximum of the intensity measure (IM) (e.g., 3-s gust wind speeds) for each event and for each location (or census tract) is estimated, and then the fragility (or vulnerability) curves (or surfaces), which are usually developed considering a wind time history of short duration, will be applied to estimate the structural damage and monetary loss, and consequently, the aggregated loss for a portfolio of structures is calculated. This approach has the merits of simplicity for loss calculation and the potential to be integrated into performance-based hurricane engineering (PBHE). However, its crude representation of the hurricane event, based on only one instance of IM for the wind velocity and a short time history analysis, cannot account explicitly for damage resulting from prolonged winds at slightly lower intensities. That is, this approach neglects the effect of the hurricane duration. Strong hurricane winds for a site could last several hours or days and the approach will likely underestimate the hurricane risk. Another method is the one adopted in HAZUS HM, which employs a simulation-based strategy by considering the hurricane characteristics and its movement along the track at multiple time instants, with a certain time increment (e.g., 15 minutes). This method explicitly incorporates the duration of high winds using the simulated tracks in its risk analysis. However, few of the existing studies have explored the possible differences in the estimation of risk resulting from these two approaches. To fill this gap, we utilized an improved physics-based hurricane full track model developed by the authors recently. Then, a portfolio of structures, consisting of 26516 wooden residential buildings in Lake Charles, LA is established as a testbed example. The event-based and annual regional loss estimations are carried out using the two approaches introduced previously. Moreover, the uncertainties in the hurricane hazard modeling will be effectively captured, propagated, and evaluated. Finally, a set of risk metrics will be compared and discussed, and the recommendations for future regional risk analysis due to hurricanes will be presented.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A LARGE-SCALE SYNTHETIC 3D POINT CLOUD DATASET FOR VISION-BASED BRIDGE CONDITION ASSESSMENT

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ABSTRACT

Bridges are a necessary part of the society, and their inspections play the crucial role in maintaining their integrity. Currently, the inspections are mainly performed visually by human inspectors, which is known to be time-consuming and labor-intensive. To improve the efficiency of the process, and eventually to automate the entire process of visual inspection, 3D visual recognition of bridge inspection scenes should be performed based on point cloud data. While existing research demonstrates promising results for automatically recognizing critical bridge components from point cloud data, the generalizability and levels of detail of the recognition results are limited. To realize high-performance 3D visual recognition of bridge inspection scenes, algorithms should be trained using large-scale annotated point cloud datasets that represent the target application scenarios.

This research investigates an approach for developing large-scale synthetic point cloud datasets that represent data collection scenarios during bridge inspection. The proposed approach proceeds in four steps: (1) random generation of different types of bridges in computer graphics environments, (2) sampling of camera trajectories that represent data collection scenarios during bridge inspection, (3) 3D reconstruction using Structure from Motion (SfM) applied to rendered synthetic images, (4) automated annotation of reconstructed point cloud using ground truth masks obtained with synthetic images. The generation of synthetic bridge environments in this research is based on Random Bridge Generator (RBG), a platform that can generate synthetic environments for bridge inspection randomly, automatically and procedurally. Besides, this research proposes to store point uncertainty information defined by the error between the ground truth depth and the depth calculated by the SfM results. Prior to training, thresholds can be applied to this uncertainty information to control the levels of outliers in the dataset. This research demonstrates the proposed approach by generating point cloud datasets for two data collection scenarios: (1) collection of dense point cloud data of bridge components for detailed assessment, and (2) collection of sparse point cloud data of the entire bridge with potential applications for Bridge Information Modeling (BrIM) and autonomous inspection planning. The effectiveness of the generated datasets is investigated by training 3D semantic segmentation algorithms, and evaluating the performance on real and synthetic point cloud data. The proposed approach for point cloud dataset generation will facilitate the development of generalizable and high level-of-detail 3D recognition algorithms toward autonomous bridge inspection.

Phase change materials (PCMs)-based multifunctional architected construction composites
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UTILIZATION OF PHASE CHANGE MATERIALS TO CONTROL ASPHALT PAVEMENT TEMPERATURE AND RUTTING

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[4]Texas A&M University

ABSTRACT

Reducing asphalt pavement temperature during the summer offers significant benefits in relation to the mitigation of rutting problems. This study experimentally and numerically investigated the feasibility of using a phase-change composite material to regulate asphalt temperature, which in turn controls pavement rutting. The phase change composite consists of silicon dioxide (SiO2) as the shell and polyethylene glycol (PEG) as the phase change material; it was used to replace a portion of the fine aggregate in asphalt mixtures. Different asphalt concrete mechanical tests were conducted, and the results showed that the addition of the PEG/SiO2 composite only had slight negative impacts. The effectiveness of the PEG/SiO2 modified asphalt concrete for pavement temperature regulation was subsequently demonstrated through a lab-scale, indoor heating test using slab specimens with different PEG/SiO2 dosages and moisture conditions. A 3-D heat transfer modeling technique was applied to model the temperature field of the slab during the heating test. Finally, to relate pavement temperature to rutting, a systematic numerical modelling framework to quantify the effects of phase change material on the early-stage rutting performance of asphalt concrete pavement was proposed. The results showed that phase-change materials can be used in asphalt concrete to control pavement temperature and rutting.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PATTERN RECOGNITION IN OFFSHORE WIND TURBINE DYNAMICS: UNVEILING FATIGUE AND DAMAGE SIGNATURES

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ABSTRACT

The escalating prominence of wind power as a primary source of renewable energy in the United States underscores the critical role that offshore wind turbines (OWTs) will play in meeting the target energy demands. The structural health monitoring of these turbines is crucial, particularly given the harsh marine environments and varying operational conditions they face. While prior studies emphasize the importance of fatigue assessment in wind turbines through dynamic monitoring, existing approaches often fall short in comprehensively considering the impact of diverse variables on fatigue calculations within offshore wind turbine towers. Many findings rely on numerical model experiments, revealing a gap that necessitates more sophisticated and contextually relevant research in real-world applications. This study addresses this gap by analyzing the dynamic response of a 6MW offshore wind turbine using monitoring data collected from sensors (e.g., strain gauges, accelerometers, etc.). The objective is to classify and characterize the major causes and sources inducing damage and fatigue in these structures. The methodology employed in this study involves investigating the strain signals to identify patterns associated with different fatigue and damage occurrences, giving insight into the structural integrity of OWT. By utilizing actual operational data from the Block Island Wind Farm, this research ensures an accurate representation of the structural stresses experienced by OWTs. As a result, the monitoring approach adopted in this investigation not only enhances our comprehension of the dynamic forces affecting OWTs but also facilitates more accurate predictions of fatigue-induced damage, thereby contributing to the advancement of predictive maintenance strategies in offshore wind turbines.

A GENERALIZED PHYSICS-INFORMED POLYNOMIAL CHAOS FRAMEWORK FOR SURROGATE MODELING AND UNCERTAINTY QUANTIFICATION

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ABSTRACT

Polynomial chaos expansion (PCE) is a widely adopted surrogate modeling method primarily employed in uncertainty quantification (UQ) and, more recently, in the field of machine learning (ML). PCE surrogate models are trained using a limited number of deterministic simulations from computationally expensive models to yield pointwise predictions within the design space. However, ensuring an accurate approximation of the underlying model may require a considerable number of computationally expensive simulations, which is often challenging with physics-based models. To reduce the training data requirement for precise predictions, we can supplement the limited data with the known physics of the model, thereby improving the accuracy and computational efficiency. This work presents a novel generalized physics-informed PCE framework for incorporating various types of known physical constraints, such as initial and boundary conditions, governing partial differential equations, and inequality-type constraints (e.g., monotonicity, convexity, non-negativity.) We demonstrate that the proposed method shows a high level of accuracy while significantly decreasing the need for expensive simulations run for training. Furthermore, the predictions adhere to the physical laws throughout the entire design space, making it ideal for UQ and ML applications involving physical models.

Analysis of heritage structures: Tools and methods for assessing unknowns in historic monuments and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL CHALLENGES OF WORKING WITH EXISTING CAST-IRON COLUMNS

Fatemeh Shirmohammadi[1], Aydin Pekoz[1] and Kevin Poulin[1]*

[1]Simpson Gumpertz & Heger

ABSTRACT

The use of cast-iron columns was popular from the early 18th century to the early 20th century in the United States and provided a good alternative to wood columns which are, typically, more vulnerable to fire. The cast-iron columns are inherently brittle and not weldable; therefore, they were phased out by structural steel. Still, there are many existing buildings today that use such columns. These buildings are aging, and their rehabilitation and restoration often require strengthening of existing cast-iron columns. Strengthening strategies typically depend on the shape of the columns and their load capacity requirements. These strategies include but not limited to:

(i) Steel jackets: This technique is commonly used to increase the strength and ductility of the circular concrete columns. Steel jacketing can also be considered to strengthen a cast-iron column. This approach, however, requires complex detailing and load transfer from the column to the jacket.

(ii) Fiber reinforced polymers (FRP): The FRP wraps have been used in the United States to strengthen reinforced concrete and masonry structures for more than 30 years. American Concrete Institute (ACI) Committee 440 provides design guidelines and limitations for the applicability of FRP wraps to strengthen concrete/masonry elements. However, there is no guideline that specifically focuses on strengthening cast-iron columns with FRP. Over the last decade, numerous experimental and numerical studies have been conducted to capture the behavior of cast-iron columns strengthened using FRP wraps. Overall, these studies have shown that strength and stiffness of cast-iron columns can be enhanced significantly.

(iii) Reinforced concrete jackets: Creating a reinforced concrete cage around the existing cast-iron column increases the column strength, as well as its ductility. Similar to steel jacketing, this method, however, requires complex detailing for load transfer between the concrete jacket and the cast-iron column. In addition, a concrete jacket significantly increases the cross-sectional dimensions of the column, which may not be architecturally acceptable.

For historic buildings with existing cast-iron columns, another challenge is to calculate the allowable load carrying capacity of these columns. In this presentation, the authors will evaluate several available methods to calculate the allowable axial load in cast-iron columns. They will also summarize advantages and disadvantages of the cast-iron column strengthening strategies mentioned above. They will present a case study from a recent renovation project, for which above techniques have been evaluated.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances on life-cycle of structures and infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FATIGUE LIFE OPTIMIZATION OF FLOATING OFFSHORE WIND TURBINE MOORING LINES USING OPENFAST AND MLIFE

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ABSTRACT

Abstract:
The key objectives of this work are to utilize OpenFAST and MLife to optimize Floating offshore wind turbines (FOWTs) designs by maximizing mooring line fatigue life and generating a database of simulated mooring line fatigue loads across various operating conditions. MLife consists of a collection of MATLAB scripts specifically designed for the analysis of fatigue life and statistical parameters associated with one or more time series. It is important to acknowledge that the development of this software can be credited to Greg Hayman, who is associated with the National Renewable Energy Laboratory (NREL). Utilizing time series data extracted from OpenFAST modules such as ElastoDyn, BeamDyn, SubDyn, and MoorDyn served as the input files for running MLife. In addition, the input files included data related to environmental factors, such as time series information for both wind speed and wave elevation. This facilitates the analysis of fatigue behavior in the mooring system. However, the outputs of this project encompass load range histograms, damage equivalent loads, fatigue damage rates, lifetime damage, and time until failure of the nylon mooring system. Moreover, the combination of OpenFAST for simulating loads on mooring lines in floating offshore wind turbines and MLife for fatigue analysis brings valuable contributions. This synergy can lead to optimized mooring component design, striking a balance between cost and structural reliability. Additionally, it can enhance FOWTs availability by providing insights for informed operations and maintenance practices.
Keywords: FOWTs, Nylon mooring system, Fatigue analysis, OpenFAST, MLife.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MOLECULAR MECHANISMS UNDERLYING THE PEG-TREATMENT OF WOOD CELL WALL COMPONENTS

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ABSTRACT

Treatment of wood cell wall with polyethylene glycol (PEG) is a widely used technique by archaeologists and conservators to consolidate waterlogged archaeological wooden artifacts such as the Swedish warship Vasa and Henry VIII's warship the Mary Rose. PEG treatment is shown to effectively stabilize the wood structure and prevent extreme shrinkage and structural collapse that can occur during uncontrolled drying processes. Despite its widespread use, the precise molecular origins and mechanisms of this consolidation behaviour are not fully understood and are still subject to further research and interpretation.

In this work we employ a novel, iterative hybrid all-atom molecular dynamics and grand canonical Monte-Carlo (GCMC) simulation to provide a molecular-level understanding of the impact of PEG treatment on the hygromechanical properties of wood cell wall components. Our investigation focuses on analyzing and comparing the hygroscopic properties of different cell wall constituents treated with PEG. The simulation systems include amorphous mixtures of cellulose, hemicellulose (unsubstituted xylan), uncondensed lignin (coniferyl and sinapyl) and fibre-matrix interphase treated with a varying amount of PEG. The mixtures of PEG-treated biopolymers are equilibrated under a range of relative humidity from fully dry to saturation and then characterized by measuring porosity, pore size distribution, mechanical properties, and hydrogen bonding network.

Our findings reveal PEG treatment is particularly effective on polysaccharide components of wood. In amorphous cellulose and xylan mixtures, as well as in cellulose nanocomposites, there is a notable reduction in moisture adsorption and swelling at museological conditions, followed by an unfavourable increased sorption/swelling at high relative humidity, highlighting a crossover phenomenon in hygroscopicity. In comparison, lignin mixtures show almost no moisture/swelling reduction. Moreover, all PEG-treated samples exhibit PEG induced weakening due to breakage of the polymer-polymer hydrogen bonding network as a result of PEG adsorption. Two key mechanisms are identified explaining the consolidation effect of PEG: first, PEG fills the porosities of the amorphous structure thus diminishing sorption sites; second, the cell wall structure prohibits PEG from further swelling thus constraining water sorption. The insights from this study serve as a guide for the design of novel consolidant materials by identifying the key mechanisms at play.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN PERIDYNAMIC MODEL FOR FRAGMENTATION IN THE CRUSHING OF SOLIDS

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ABSTRACT

A technique is proposed for reproducing particle size distributions in three-dimensional simulations of the crushing and comminution of solid materials. The method is designed to produce realistic distributions over a wide range of loading conditions, especially for small fragments. In contrast to most existing methods, the new model does not explicitly treat the small-scale process of fracture. Instead, it uses measured fragment distributions from laboratory tests as the basic material property that is incorporated into the algorithm, providing a data-driven approach. The algorithm is implemented within a nonlocal peridynamic solver, which simulates the underlying continuum mechanics and contact interactions between fragments after they are formed. The technique is illustrated in reproducing fragmentation data from drop weight testing on sandstone samples.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A SUB-STRUCTURING APPROACH TO OVERCOME MODEL LIMITATIONS FOR INPUT-STATE ESTIMATION OF OFFSHORE WIND TURBINES

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[2]ETH Zurich

ABSTRACT

In this work, the Augmented Kalman Filter (AKF) is used for input-state estimation of an offshore wind turbine (OWT) on a monopile foundation. As the focus of this work is on the properties of the tower and foundation, a suitable substructure is studied. The advantage of this approach is that it avoids limitations related to the modelling of the soil-structure interaction (SSI) and the Rotor-Nacelle Assembly (RNA), thus significantly reducing model uncertainties. At the same time, the approach requires that the interface forces to the substructure are estimated. This research is motivated by the increasing demand for renewable energy and the need to maximise the operational lifespan of OWTs. To aid this goal, OWTs are installed with sensors (typically accelerometers, strain gauges or inclinometers), which allow for the continued monitoring of an OWT's structural health. To save on cost and for higher data quality, these sensors are typically installed at easily accessible locations, e.g., along the tower. However, it is usually of interest to measure the response at submerged locations or within the foundation, where fatigue can be critical. To address this challenge, virtual sensing has emerged as an effective solution, whereby a system model and measurements are leveraged to estimate the response at unmeasured locations, as well as the unknown inputs to the system. Nevertheless, the quality of the estimated results depends on the accuracy of the chosen model, for which various complexities exist, making this a challenging task. Two of which are the lack of information required to model the RNA, and the high uncertainty associated with the SSI. Therefore, the primary focus of this work is to avoid these limitations, by 'cutting' the OWT at the top of the tower and the ground level. To define the model, the resulting substructure then only requires geometries and material properties for the monopile and tower - information which is often known with greater certainty. A numerical case study is presented to investigate the accuracy of the proposed approach for input-state estimation of a 15 MW OWT. A series of commonly used setups involving accelerometers and inclinometers are used and the effects on the predicted fatigue life of the structure are discussed. The proposed approach is shown to be an effective solution for input-state estimation of OWTs, when the RNA or SSI are unknown or associated with significant uncertainty.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL INVESTIGATION OF SHEAR BAND FORMATION DURING OLIVINE TRANSFORMATION USING INTEGRATED REPRODUCING KERNEL PARTICLE AND CRACKING PARTICLE METHOD

S. Sindhusuta[1], Sheng-Wei Chi[1] and Craig Foster[1]*

[1]University of Illinois Chicago

ABSTRACT

The physical mechanisms triggering deep-focus earthquakes remain a puzzle for the scientific community. Many studies propose that the formation and self-alignment of shear bands consisting of nanocrystalline spinel formed in olivine is responsible for the formation of macrocracks and failure of samples, which ultimately triggers deep-focus earthquakes [1] . However, the studies are limited to small-length-scale experiments in the laboratory; the self-organizing mechanism from small fractures or faults to form a large fault leading to failure cannot be directly studied in the laboratory.

The objective of this work is to numerically study the role of the formation of nano shear bands of spinel behind the failure of olivine samples in high-pressure experiments and, ultimately, the role of phase transformation behind the generation of deep-focus earthquakes. A thermo-mechanical model approach has been taken to model the phase transformation behavior. A thermodynamically consistent multiscale model, based on Mahnken et al., 2015 [2] , has been developed to capture the evolution of phase transformation in olivine under different pressure and temperature conditions.

Further, the Reproducing Kernel Particle Method (RKPM) integrated with the Cracking Particle Method [3] has been employed to model thin nano shear bands more accurately. The strain localization due to the shear band formation is enhanced by a set of discontinuous kernels with only the degree of freedom tangent to the shear band. This methodology is initially validated for shear band formation under pure compression scenarios with plastic softening and subsequently applied to a 2D model featuring multiple grains where the formation of shear bands during olivine transformation under high pressure is studied. This model explicitly investigates the formation of shear bands during the olivine-spinel transformation, offering insights into the failure mechanisms under high-pressure conditions during the olivine-spinel transformation. By combining these advanced numerical simulations with experimental insights, this research will shed light on the intricate interplay between phase transformation, nano shear band formation, and deep-focus earthquake generation.

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Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE AND DEEP LEARNING APPLICATIONS FOR DAMAGE QUANTIFICATION ON REINFORCED CONCRETE COLUMNS

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ABSTRACT

This research explores the use of classical and modern machine and deep learning techniques to quantify the damage in the columns of a reinforced concrete (RC) frame infilled with a masonry panel. The study focuses on a large-scale infilled RC frame subjected to in-plane gravity and lateral loads. Photographs of the structure at various damage levels of known inter-story drift ratio are used to train four classical machine-learning techniques, i.e., Linear Regression, Support Vector Machines (SVM), Regression Trees, and Ensemble Trees, as well as four deep learning algorithms, i.e., Simple Convolutional Neural Networks (CNN), CNN with attention, Deep Learning with engineered predictors and a Hybrid algorithm that combines the engineered features with raw image data in a CNN. Once the algorithms are trained, the error analysis indicates that the best classical machine learning algorithm that applies to this dataset is the SVM. In terms of deep learning algorithms, the most suitable is the hybrid model. Overall, the latter provides the best estimations according to the error metrics. The potential use of these algorithms for assessing structures that deteriorated due to aging, extreme loading events, or both is further discussed.

NUMERICAL MODELING OF TRUCK-ELECTRIFICATION-INDUCED EXCESS FUEL CONSUMPTION IN HIGHWAY FLEXIBLE PAVEMENTS

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ABSTRACT

The onset of new technologies in the freight industry is expected to exacerbate the deterioration of the US highway network as the incorporation of heavy battery packs could lead to increased axle load demands, load redistribution and increased torque power.

According to the American Society of Civil Engineers (ASCE), one in five miles of public roadways is currently in poor condition (2021). As the unevenness of a pavement surface increases, the vertical oscillation of mechanical systems such as vehicles induce a dynamic change in the applied load. This phenomenon, known as dynamic wheel loading (DWL) is greatly influenced by the roughness of the surface profile, traveling speed, applied axle load and the mechanical properties of the vehicle. The increased weight of electric trucks then is expected to aggravate load amplification and lead to higher deterioration rates. Road roughness in turn, induces excess vehicle fuel consumption as mechanical systems dissipate more energy, affecting the environmental and cost assessment of flexible pavement life cycle.

In this study, the excess fuel consumption of an electric semi-trailer truck is numerically simulated for different battery pack locations, battery pack weights, traveling speeds, and road roughness conditions and are compared with a reference case to assess the changes in energy demand. Multi-track road roughness profiles are artificially generated based on a target International Roughness Index (IRI) to excite a mechanical three-dimensional semi-truck model using an integrated truck-pavement system formulated in MATLAB Simulink (Liu & Al-Qadi, 2021). The dynamic responses of the mechanical system are recorded to generate Dynamic Loading profiles and estimate the excess fuel consumption.

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Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING BUILDING DAMAGE ASSESSMENT IN POST-DISASTER SCENARIOS USING META DATA-ENRICHED TRANSFORMER MODELS

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ABSTRACT

In the aftermath of a large-scale disaster, the rapid and accurate identification of building-level damage is essential for effective response and recovery efforts. Towards this, recent advances in deep learning architectures have identified remote sensing data, such as optical images and InSAR (interferometric synthetic aperture radar) images, as valuable data sources. However, achieving sufficient accuracy for multiclass building damage assessment (BDA) for practical applications, solely through satellite images remains a challenge. Besides image data, another important factor accounting for the intensity of the disaster (e.g., wind speed, shake intensity, etc.) has not received much attention for multiclass BDA. To address this, our study introduces a novel framework that combines high-resolution post-disaster satellite images with publicly available metadata, including geographical attributes, disaster intensity variables, and other building properties. By training state-of-the-art transformer models on both images and metadata, the research explores the extent of improvement achieved by integrating metadata into the model training process. The study also investigates the model's capacity to predict building damage across different disaster types to achieve better generalizability. This exploration is pivotal in contributing to a more adaptable and robust approach in post-disaster BDA.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in resilience analytics and sustainable infrastructure: Bridging theory and practice
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RESILIENCE DEFICIT INDEX: AN ALTERNATIVE WAY TO QUANTIFY RESILIENCE

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ABSTRACT

Resilience is typically defined by the area under the functionality curve normalized by reference time, which is often arbitrarily assumed. This dimensionless quantity is referred to as resilience index. However, the use of an arbitrarily defined reference time can introduce bias in the quantification of resilience. This presentation presents a novel way of quantifying the resilience of structures, without having to define the reference time. Instead, it relates the area above the functionality curve to resilience using normalized values and units. The use of normalized values is helpful in comparing the resilience of different structures in a way similar to resilience index and the units help convey information about the performance of structures in quantifiable terms without any bias. The efficiency of the proposed resilience deficit index is demonstrated with a case study considering a typical URM warehouse building in California.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF THE PARTICLE SHAPE ON THE ELASTIC ANISOTROPY OF GRANULAR MATERIALS

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ABSTRACT

The mechanical response of granular continua is well-known to reflect their microstructural characteristics (e.g., contact distribution, dispersion of particle size and shape). The directional properties of many of these factors are often quantified through tensors referred to as fabric. One key factor influencing the granular fabric and therefore the behavior of granular continua, is the shape of the constituent particles and the associated contact areas between them. For instance, spherical particles tend to produce isotropic packing structures, resulting in uniform elastic properties in all directions. In contrast, non-spherical particles can lead to anisotropic elastic properties. It is particularly due to the variation in the contact areas with varying shapes and orientations, leading to differences in the interparticle force chains and therefore to elastic anisotropy. To understand such an effect, Discrete element simulations (DEM) were performed to evaluate the role of the contact area fabric on the elastic anisotropy of granular assemblies consisting of ellipsoidal particles, while inhibiting irreversible mechanisms via the probing technique proposed by Calvetti (2003)1. First, an analytical expression is obtained to quantify the elastic stiffness of the ellipsoidal particles, which is further compared with the DEM simulations. The obtained analytical expression strongly reflects that the elastic anisotropy of assemblies made by non-spherical particles depends both on aspect ratio and contact area and is then confirmed against triaxial compression test simulations on assemblies characterized by a crystalline packing. Remarkably, a slightly modified form of this expression was found to fit a much wider range of assemblies constating of particles with varying aspect ratios and orientations, as demonstrated when comparing it to triaxial simulations involving randomly placed ellipsoids. To model such inherent shape effects as well as stress-induced effects on the elastic anisotropy, it was shown that existing constitutive laws (e.g., Houlsby et. al (2019)2) needs to be enhanced. Therefore, a fabric-enriched continuum framework is proposed which considers the inherent fabric effects due to shape and accounts for the adaptive fabric contributions under purely elastic conditions. The enhanced model shows significant benefits in terms of predicting the inherent anisotropy for different aspect ratios and particle orientation, as well as for quantifying stress-induced nonlinearity.

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Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOWARDS DEVELOPMENT OF LOW-CARBON CONCRETE VIA HIGH-VOLUME CEMENT REPLACEMENT WITH RECYCLED GROUND GLASS POZZOLAN

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ABSTRACT

The energy-intensive clinkering process renders cement manufacturing one of the largest industrial CO2 emitters responsible for 8% of global CO2 emissions and hence a prominent climate change threat. Towards reducing the carbon footprint of concrete, the replacement of cement with supplementary cementitious materials (SCM) stands out as a practical and effective approach without sacrificing concrete performance. The low local availability of high-quality SCMs and deduction in the supply of industrial byproducts, such as fly ash, give rise to new challenges. According to the 2018 data from the Environmental Protection Agency and Glass Packaging Institute, only 31.3% of the 12.3 million tons of waste glass in the United States was recycled and the remainder is often buried in landfills or stockpiled resulting in wasting resources and environmental pollution. In light of the high silica content and amorphous structure, recycled ground glass can trigger pozzolanic reactions in the matrix of cement making it suitable to be used as a pozzolan for high-quality concrete design, while its role in cement modification and concrete performance remains unclear. This study aims to develop low-carbon concrete by leveraging high-volume recycled ground glass pozzolan (RGGP) and tailoring its interaction with cement hydration. The pozzolanic reactivity of two RGGPs and their roles in modifying the hydration kinetics and reaction products were investigated through isothermal calorimetry, quantitative X-ray diffraction, thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), and thermodynamic simulations. The influence of RGGP on the shrinkage behavior and mechanical strength of concrete was also studied.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SOLVING TRANSIENT STRUCTURAL SOURCE INVERSION PROBLEMS USING RANDOMIZED TRUNCATED SINGULAR VALUE DECOMPOSITION

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ABSTRACT

Structural source inversion entails estimating unknown input signals from noise-polluted vibration response measurements via inverse methods. Applications of source inversion include multi-input multi-output (MIMO) control problems for lab-based vibration testing and force reconstruction for system identification or impact monitoring. Solving inverse problems in the time domain is challenging, computationally demanding, and—without automated regularization—user-intensive. To address the computational demands of these inverse problems, this work proposes a truncated singular value decomposition (SVD) regularized inverse approach that leverages matrix-free randomized linear algebra.

The recent growing popularity of the randomized SVD has spurred a revisit of many large-scale inverse problems in structural dynamics. Its popularity is in large part due to, first, the potentially massive computational savings compared to the full or partial factorization of a large matrix and, second, its seamless integration into the regularized inverse solution via the truncated SVD (TSVD). Since time domain structural dynamics control inverse problems can be large and highly ill-conditioned, these two characteristics make the randomized SVD an ideal candidate for solving them.

One unaddressed issue with replacing the exact SVD factorization in the TSVD inverse solution with the randomized SVD factorization is that the selected truncation rank needs to be known a priori in order to determine the number of random samples needed to compute the randomized SVD. Since the "best" truncation rank is unknown and will depend on the measurement noise, this assumption is extremely prohibitive. In order to make the randomized TSVD a practical alternative, some form of automated truncation selection is needed to guide the construction of the randomized SVD. This work addresses this issue by combining Morozov's discrepancy principle and the randomized SVD range finding algorithm in order to automatically select the rank and number of random samples. As this work will show, the additional cost of the proposed automatic truncation selection is negligible at its best.

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MULTISCALE STRUCTURAL OPTIMIZATION FOR APPLICATIONS IN THERMAL STABILITY AND ACTUATION

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[1]Drexel University

ABSTRACT

A multiscale optimization framework for the design of multifunctional structures subjected to mechanical and thermal loads is presented. By exploiting the unique potential of spatially varying microstructures, structures are produced with enhanced structural stability and actuation capabilities. The methodology hinges on a three-phase material design within the microstructure, composed of materials with high and low coefficients of thermal expansion (CTE), and void material, to achieve a spectrum of expansion coefficients. By optimizing the layout of these microstructures within the greater structure, it is possible to induce desired thermomechanical behaviors, accommodating extreme conditions and precise deformations.

To address the computational challenges inherent in the design of complex multiscale structures, the research utilizes deep neural network surrogate models for numerical homogenization, significantly reducing the computational complexity of the multiscale model. The surrogate models predict effective material properties, which are validated against traditional finite element analysis. Results of the full finite element model, the multiscale finite element model, and the deep neural network model are also compared. Design optimization is performed with a mix of compliance objectives subjected to deformation constraints. The balance of structural compliance, targeted deformation, and volume constraints are shown to play a key role in the design of multifunctional structures under thermomechanical loading. Presented examples validate the optimization approach for structural stability, where the target displacement is zero, and thermal actuation, where the target displacement is non-zero.

Advances in bridge health monitoring: Data-driven and machine learning methods, indirect monitoring, crowdsourced mobile sensing
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FAILURE PREDICTION OF DAMAGED MEMBERS USING A DEEP NEURAL NETWORK (DNN)

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ABSTRACT

This research presents experimental and analytical works to develop a deep neural network (DNN) that can predict failure for structures with some damage or faulty connections. A simple cantilever beam will be partially cut to model structural failure, and dynamically tested to collect training data. Another application is a 23.5 feet long and three and 3.75 feet high truss bridge. Physical damages will be modeled by loosening bolts at selective joints. The collected data is used to train the DNN model. The challenge of limited data size from the experiments is overcome by incorporating simulation data. Several models with different fidelity will be created for each structure. Eventually, the effect of model fidelity on the accuracy of damage prediction by the DNN model will be investigated.

The benefit of using a deep neural network (DNN) is that calculation times will be reduced and failure prediction will be more accurate. Another motivation for using the DNN model is that faulty connections can be more accurately modeled with decreased analysis time. This promising new model also has the application to provide dynamic failure prediction for various structures and cost-effective decisions to repair deteriorated/damaged structures.

Keywords: Deep Learning, Damage identification, Structural Analysis

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Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCED COMPUTATIONAL AND DEEP LEARNING ALGORITHMS FOR MODELING AND DESIGN OF MATERIALS

Soheil Soghrati[1], Balavignesh Vemparala[1], Salil Pai[1] and Pengfei Zhang[1]*

[1]The Ohio State University

ABSTRACT

This presentation discusses the development and implementation of an AI-driven computational framework for simulating the mechanical behavior and design of materials with complex microstructures. In the first part of the presentation, we present a geometry reconstruction algorithm utilizing virtual packing and optimization techniques for synthesizing heterogeneous material microstructures. Additionally, an AI-based approach relying on a Deep Convolutional Degenerative Adversarial Network (DCGAN) is developed for the virtual reconstruction of digital twins of human bone. To simulate the mechanical behavior of resulting microstructural models, finite element (FE) meshes are generated using the Conforming to Interface Structured Adaptive Mesh Refinement (CISAMR), which is a non-iterative algorithm that transforms an initial structured grid into a high-quality conforming mesh. In the second part of the presentation, we show how these microstructure reconstruction and meshing algorithms serve as a powerful engine for generating the training data for AL/ML applications aimed at predicting the performance of materials/structures. In the first example, we show how a CNN-based model can be trained with the data generated using this framework to predict the failure response of steel pipes subjected to pitting corrosion. We also introduce a new AI-based technique, named the Deep Learning-Driven Domain Decomposition (DLD3) method, that can be used as a surrogate for FE analysis for a wide array of problems. Unlike pure scientific AI/ML models, this patented algorithm is highly generalizable and can predict the deformation response of problems with arbitrary geometries and loading. Moreover, compared to FEM, it significantly reduces the operational and computational by obviating the complexity of the modeling process (no need for mesh generation) and reducing the simulation time.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FIELD DEPLOYMENT VALIDATION OF A LOW-COST AND HIGH-PRECISION DISPLACEMENT SENSOR COMBINING MILLIMETER-WAVE RADAR AND ACCELEROMETER

Zhanxiong Ma[1], Kyuwon Han[1], Jaemook Choi[2], Jigu Lee[1], Ohjun Kwon[1], Hoon Sohn[1], Jingxiao Liu[3], Doyun Hwang[3], Jatin Aggarwal[3], Hae Young Noh[3], Enjian Cai[4] and Yi Zhang[4]*

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[3]Stanford University
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ABSTRACT

Abstract: Although displacement measurements are critical for many civil infrastructure applications, accurate monitoring of structural displacements remains a challenge, especially for medium/small-scale structures with only millimeter-scale vibrations. The authors previously proposed a structural displacement estimation technique using collocated accelerometer and millimeter wave radar measurements, and the technique can achieve sub-millimeter accuracy [1]. Based on this technique, this study developed a displacement measurement sensor that integrates a low-cost millimeter-wave radar, an accelerometer, and a microprocessor unit. With a total cost of less than 1000 USD, the developed sensor still measures displacement well with a low error (< 0.5 mm) and a high sampling rate (100 Hz). In addition, the developed sensor achieves wireless data transmission based on a wireless local-area network (WLAN), which makes it more convenient for practical applications. To fully validate the performance of the developed sensor, field tests were conducted on nine different structures, including four highway bridges in San Jose, USA, a parking structure in Stanford, USA, a highway bridge in Daejeon, South Korea, and three highway bridges in Weifang, China. For all structures, the developed sensor was able to accurately measure displacements with a maximum root mean square error (RMSE) of less than 0.06 mm, compared to the ground-truth displacement measured by a laser Doppler Vibrometer.

Keywords: Displacement measurement, millimeter wave radar, accelerometer, data fusion.

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Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A LIFE-CYCLE COST ANALYSIS TO DETERMINE THE EFFECTIVENESS OF PRESTRESSED CONCRETE POLES AGAINST AGING AND COMBINED WIND-SURGE-WAVE INDUCED LOADS

Saeed Sohrabi[1], Yousef Darestani[1], William Pringle[2], Daniel Dowden[1] and Payman Dehghanian[3]*

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ABSTRACT

In the US, power transmission systems are commonly supported by lattice towers or wood poles. Land acquisition issues often make towers an unpopular choice in urban areas. Wood poles are not favorable either due to their high rate of decay. To address this issue, decayed transmission poles are commonly replaced by durable Prestressed Concrete (PC) poles. Considering the recent increase in the number of PC poles in the transmission system, it is imperative to investigate their effectiveness over the service life of transmission lines. A comprehensive life-cycle analysis requires a probabilistic wind-surge-wave model along with PC pole fragility models. However, the current literature does not offer such models. To address such issues, first, a probabilistic wind-surge-wave model is developed using 10,000 years of synthetic storms for the Gulf of Mexico. The dataset comprises about 5,000 storms. The storms are categorized based on their maximum wind speed and then return periods for various wind speed levels are determined by counting the number of storms in each wind level. As storm events follow a Poisson point process, the Cumulative Distribution Function (CDF) of the exponential distribution is adopted to determine storms' annual exceedance probability (AEP). Furthermore, 50 storm samples are selected from the 5,000-storm ensemble such that the CDF of the model remains identical to the original dataset and the storms' spatial distribution is kept uniform. For the 50-storm ensemble, surge and wave levels are estimated via ADCIRC+SWAN platform. Second, a Monte Carlo simulation is used to develop a set of age-dependent PC pole fragility models against wind-surge-wave induced loads. The fragility models show that PC poles, unlike wood poles, are not significantly affected by aging and deterioration. Finally, the probabilistic wind-surge-wave and fragility models are used to perform a comprehensive life-cycle analysis considering direct and indirect socio-economic costs for a real transmission line serving around 3,000 customers in Pascagoula, Mississippi. The results show that when PC poles are compared with their equivalent wood poles, for the first few decades, the incurred costs are not significantly different. However, for longer periods, the difference becomes significant, where PC poles in a 70-year period, save more than 8 million dollars (30% less socio-economic costs). This study provides a framework to estimate life-cycle costs for coastal infrastructure systems subjected to wind-surge-wave effects and provides insights to keep the coastal infrastructure resilient and cost-effective against future storm hazards.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTIPLEXED LASER ULTRASONIC IMAGING VIA THE LINEAR SAMPLING METHOD

Jian Song[1], Fatemeh Pourahmadian[1], Todd Murray[1] and Venkatalakshmi Narumanchi[1]*

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ABSTRACT

This research investigates the potential of multiplexed excitation in laser ultrasonic testing to enhance subsurface imaging by way of non-iterative full-waveform tomography. More specifically, the objective is to improve the quality and fidelity of reconstructions obtained via the Time-domain Linear Sampling Method (TLSM) from noisy test data. In an earlier study [1], we demonstrated that the TLSM indicator is relatively sensitive to (random and systematic) perturbations in measurements, resulting in the emergence of artifacts in the constructed images. In this work, we propose an experimental approach based on spatial multiplexing within the context of laser ultrasonics to maximize the signal-to-noise ratio (SNR), and subsequently, augment the imaging ability of the TLSM indicator. Spatial multiplexing involves division of a single high-power laser beam into multiple smaller beams directed at different locations on the sample surface. This allows for simultaneous excitation of a specimen by multiple sources with tailored intensity and arrangement to amplify and shape the induced waveforms. The integration of multiplexing concept and imaging via the fast full-waveform indicators such as the TLSM presents several advantages, namely: (i) it naturally improves the SNR through increased input power, (ii) it expedites the inspection process by requiring fewer signal averages, (iii) it reduces the number of artifacts in the reconstructions while enhancing the image resolution by requiring smaller regularization parameters, and (iv) it fosters cost-effective testing. In light of this, we devised a series of experiments wherein a laser-trimmed metal mask is mounted and shifted on a robotic translation stage to reflect a designated illumination pattern on the sample surface. On repeating the experiments for an array of distinct multiplexing patterns, a set of ultrasonic waveforms are obtained which are used to generate the TLSM maps. The obtained results are then compared with their counterparts from conventional laser ultrasonic imaging schemes on the same specimens. The comparative analysis is further enriched by a series of detailed parametric investigations that provide a better understanding of the proposed testing solution.

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Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A DELAY COMPENSATION CONTROLLER FOR MULTI-AXIAL REAL-TIME HYBRID SIMULATION (RTHS) VIA ADAPTIVE CONTROL

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ABSTRACT

Most of the existing control designs in RTHS have focused on the time delay compensation of a single actuator. However, many practical engineering problems demand multi-dimensional compensation design, such as this benchmark problem. In this benchmark problem, the tracking control of multiple (two) actuators is required to realize the compensation of both translation and rotation degrees of freedom of the RTHS interfacing element. To address this challenge, a multiple-input-multiple-output (MIMO) control strategy is developed by dynamically decoupling the control of multiple actuators into multiple single-input-single-output (SISO) of the two actuators. This study will discuss the formulation of the dynamic decoupling procedure and its applicable range, and also demonstrate the performance of the proposed procedure based on the benchmark problem of this Research Topic.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEURAL OPERATORS FOR STOCHASTIC RESPONSE OF STRUCTURES SUBJECTED TO NATURAL HAZARDS

Dimitris Giovanis[1], Somdatta Goswami[1], Bowei Li[2], Seymour Spence[2] and Michael Shields[1]*

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ABSTRACT

Neural networks have been wisely used to learn mappings between spaces with finite dimensions. However, recent advancements in operator learning have shifted to using deep neural networks for learning operators that map infinite-dimensional function spaces. In this work, we utilize two advanced neural operators, the deep operator network (DeepONet) and the Fourier neural operator (FNO), to evaluate the stochastic response of structural systems under natural hazards like earthquake and extreme wind excitations. Our goal is to enable fast and reliable prediction of the non-linear structural response to time-varying stochastic loading and thereby rapidly assess the corresponding damage risk. The DeepONet model offers a versatile approach, allowing for flexible network architectures in its branch and trunk networks. Specifically, we propose a Fast Fourier Transform-based DeepONet (FFT-DeepONet), which incorporates Fourier modes into the trunk network via a fully connected feedforward neural network. The FNO works by parameterizing the integral kernel in Fourier space and can be seen as a DeepONet with a specific branch and trunk net architecture represented by discrete trigonometric basis functions. To validate the effectiveness and practicality of these operators, we consider two scenarios. In the first, we use the operators to predict high-rise building response in multiple bays and at multiple levels to extreme stochastic wind loading. In the second, we predict the seismic dynamic response of a six-story shear building under stochastic ground motions using our trained operators. These surrogate models predict the full time-history response with high accuracy, can be trained from a limited number of simulations, and are significantly faster than traditional numerical models.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WIND-INDUCED NONLINEAR BEHAVIOR AND COLLAPSE RISK FROM NON-STATIONARY HURRICANE WIND FIELDS

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[1]*University of Michigan*

ABSTRACT

Conventionally, the effects of hurricane winds on the built environment are modeled using stationary wind events of one-hour duration with a constant mean wind speed and direction. Although hurricane wind fields characterized by time-varying mean-hourly wind speed and direction at the building top exhibit non-stationarity during the lifetime of a storm, the conventional representation may be reasonable for linear elastic structural analysis/design. However, in performance-based wind engineering, the estimation of nonlinear structural performance during extreme winds challenges the validity of the conventional wind load representation. In this work, a fiber-based model of a 45-story archetype steel structure is considered to study the path-dependent phenomena of inelasticity (including ratcheting and potential collapse) and low-cycle fatigue (LCF) when subjected to non-stationary (NS) and non-Gaussian (NG) wind loads. In particular, the stochastic NS-NG wind loads are derived by integrating a widely used hurricane wind event simulation model [1] that outputs a pair of fluctuating wind speeds and directions, and a pressure simulation model calibrated to building-specific wind tunnel datasets. The fiber-based model can capture progressive yielding, geometric nonlinearity, buckling, damping, and LCF, up to collapse. Through peak/residual roof drifts, story drifts, fiber-/member-level yielding, and LCF-induced damage, insights are gained into damage accumulation and the growth of plasticity. Moreover, by accounting for system and load uncertainties within a stratified sampling approach, exceedance probabilities (or reliabilities) are obtained for various system and component limit states. To ensure the computational feasibility of the nonlinear response history analyses, the non-stationary loads are trimmed by excluding the initial and final segments where the peak elastic story drifts are smaller than 0.5%. In addition, for every stochastic simulation, responses are also collected corresponding to an equivalent stationary wind load vector. The equivalent stationary wind load vector of one hour duration is defined by the wind speed and direction pair that produces the largest expected peak elastic base moment among the pairs of discretized wind speeds and directions experienced by the building. Through a comparative study of wind-induced nonlinear behavior (including collapse) and the associated exceedance probabilities, this work highlights the role of hurricane wind event description with a particular focus on load duration and non-stationarity.

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MODEL FOR SIMULTANEOUS CARBONATION AND HYDRATION OF BELITE CLINKER DURING CARBONATION CURING

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ABSTRACT

Belite (β-C2S) is an important mineral in Portland cement (PC) clinker and forms the main constituent of belite cement (BC) clinkers, which have recently gained attention as a more sustainable alternative to PC. Studies regarding the hydration of BC have so far found that the hydration mechanism of BC is different from PC, although it is not known exactly how different these are. Additionally, BC has been found to respond positively to carbonation curing, which induces a densification of the hydrated microstructure and an increase in compressive strength [1]. This makes belite cements viable targets for carbonation curing as a strategy for carbon capture.

This study aims to resolve the early stages of combined hydration and carbonation of β-C2S by applying quantitative in situ X-ray diffraction (XRD) analysis to monitor the first day(s) of reaction. In situ XRD analysis has already been applied successfully to study hydration mechanisms and kinetics of several cement minerals, such as alite (C3S) and aluminate (C3A), whereas belite has received relatively less attention [2]. Using a custom-built sealed in situ XRD sample cell [3], β-C2S is reacted at room temperature in either a humid atmosphere or under elevated CO2 pressure.

From measurements on non-simultaneous hydration or carbonation of β-C2S, the optimal conditions and onset time for carbonation curing are chosen. Then, simultaneous hydration and carbonation are studied to assess the differences in phase development with and without carbonation curing and to model the effect of competitive carbonation on the hydration reaction.

Through quantification of carbonate reaction products, it was found that all three calcium carbonate polymorphs form under slightly elevated CO2 pressure and a carbonation kinetics model is proposed to quantify the carbonation rate of β-C2S. The results of this study help to form an understanding of the hydration and carbonation of belite cements and how to optimize carbonation curing as a means of improving the performance of belite cement products.

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Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FAULT FRICTION UNDER THERMAL PRESSURIZATION DURING LARGE SEISMIC SLIP

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ABSTRACT

Earthquake faults are the result of severe strain localization in rocks deep down in the earth's crust. The evolution and size of the localized deformation are controlled by the microstructure and various Thermo-Hydro-Mechanical (THM) physical processes, whose modeling is crucial for understanding earthquake nucleation and seismic energy release.

We model this challenging system using the Cosserat theory and taking into account large shear deformations during seismic slip. In particular, we use the normalized coupled system of partial differential equations that includes the THM couplings for the case of a Cosserat continuum and we perform a bifurcation analysis. Our analysis indicates that traveling shear bands are possible inside the fault gouge. Next, we perform a series of non linear mesh independent numerical analyses accounting for the influence of large displacements through an Adaptive Lagrangian Eulerian (ALE) procedure. Finally, we introduce viscoplasticity in our numerical analyses, which leads to the emergence of a "rate and state" friction phenomenology (see [2]).

Depending on the boundary conditions, our numerical results show (a) frictional restrengthening and (b) the emergence of traveling shear bands along the thickness of the fault, leading to oscillations in the fault's frictional response. This behavior is not captured by existing numerical analyses and the established models of uniform shear and shear on a mathematical plane in [1]. For this reason, we extend the classical model of thermal pressurization in [1] to incorporate different strain localization modes, temperature and pore fluid pressure boundary conditions. This extension leads to a Volterra integral equation, which is solved semi-analytically.

Our numerical findings in [3] show a good agreement with recent experimental results, that insulate thermal pressurization from other weakening mechanisms. This shows the relevance of the chosen THM mechanisms and of our models for studying fault friction and for improving the current understanding of this complex phenomenon.

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Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISCOUS REGULARIZATION IN DYNAMICAL PROBLEMS DOES NOT STOP STRAIN LOCALIZATION ON A MATHEMATICAL PLANE AND MESH DEPENDENCY

Alexandros Stathas[1] and Ioannis Stefanou[1]*

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ABSTRACT

Strain softening is responsible for mesh dependence in numerical analyses concerning a vast variety of fields in mechanics, such as solid mechanics, damage and fracture mechanics, biomechanics and geomechanics. Therefore, numerical methods that regularize strain localization are paramount in the analysis and design of engineering applications.

In [1], we examine the effectiveness of an elasto-viscoplastic, strain-softening, strain- rate hardening model to inhibit strain localization on a mathematical plane (“wave trapping”) in a Cauchy continuum.

In particular, we apply Lyapunov stability analysis, and we derive a new expression for the dispersion relation. In contrast with [2,3], we assume that both the frequency and the wavenumber are complex numbers. The dispersion relation shows that waves of infinitesimal wavelength, whose amplitude increases the fastest of all possible perturbations are present in the elasto-viscoplastic medium. This means that strain localization on a mathematical plane is possible.

Finally, in order to illustrate our theoretical results in [1], we perform extensive numerical analyses based on the available examples in literature (see [2,3]). The fully nonlinear dynamic analyses performed in [1] account for possible unloading near the yielding area. We show that strain softening in the presence of strain rate hardening and inertia leads to strain localization on a mathematical plane and mesh dependence.

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Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE MODELING OF INELASTIC MATERIALS WITH THERMODYNAMICS-BASED ARTIFICIAL NEURAL NETWORKS (TANN) AND IDENTIFICATION OF INTERNAL STATE VARIABLES

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ABSTRACT

The mechanical behavior of complex, inelastic materials with microstructure is very hard to grasp with heuristic and empirical constitutive models. An alternative approach is the use of multiscale methods based on homogenization techniques (e.g. FE2). However, these techniques are computationally intensive and prohibitive for real-scale applications.

A solution to this problem has been recently given by hard-wiring the laws of thermodynamics to the architecture of Artificial Neural Networks. This lecture focuses on this new class of physics-based, artificial neural networks, which are called TANN (Thermodynamics-based Artificial Neural Networks). In TANN, the two basic principles of thermodynamics are encoded in the network's architecture by taking advantage of automatic differentiation to compute the numerical derivatives of a network with respect to its inputs. In this way, derivatives of the free-energy, the dissipation rate and their relation with the stress and internal state variables are embedded in the architecture of TANNs. As a result, the proposed architecture does not have to identify the underlying pattern of thermodynamic laws during training, reducing the need for large datasets. Moreover, the training is more efficient and robust to noise, and the predictions more accurate. TANN enable also the automatic extraction of the dominant internal state variables from the evolving microstructural fields. By construction, these internal state variables contain the necessary information for predicting the macroscopic constitutive response of materials with complex inelastic microstructures. Finally and most importantly, the predictions of TANN remain thermodynamically consistent, even for unseen data, which is central for real-scale applications in engineering.

Several examples are presented, showing the robustness and efficiency of TANN. A large-scale boundary value problem is also solved by employing a double-scale homogenization scheme (FEM×TANN). The high performance of the homogenized model using TANN is illustrated through detailed comparisons with microstructural calculations at large scale. An excellent agreement is shown for a variety of monotonous and cyclic stress-strain paths. Finally, based on the automatically identified internal state variables, the solution of the boundary value problem at the macroscale and the double-scale homogenization scheme employed, it is shown how it is possible to reconstruct the various micro-structural fields and track their evolution.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ML-BASED VORTEX-INDUCED VIBRATION ASSESSMENT OF LONG SUSPENDERS IN LONG-SPAN SUSPENSION BRIDGES FOR AUTOMATED VIBRATION CONTROL DESIGN

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ABSTRACT

As the main structural component, the possibility of wind-induced vibration, especially vortex-induced vibration (VIV), is greatly increased due to the shape and structural characteristics of the long suspenders. To ensure the safety of the bridge and the suspenders, a complete SHM system was installed to provide real-time sensing of the bridge's operational conditions. However, the identification and perception of VIV shall require the expertise of professionals and process is labor-intensive. In light of the massively available data from the in-situ SHM system, the proposal and development of an automated strategy for VIV identification, assessment and control are much desired. This study focuses on the VIV identification and parameter assessment of suspenders, and proposes a complete methodology system, including: (a) VIV identification based on structural response characteristics as well as machine learning (ML); (b) automatic assessment of structural state parameters when VIV occurs; (c) data rules and dynamic model-driven optimization of vibration reduction strategies. The technical framework covers the whole chain of identification, whole-process analysis, assessment, and control strategies of suspenders VIV, which can provide timely data support for bridge management and maintenance. Taking the vibration events of the suspenders of a long-span suspension bridge as example, the effectiveness of the proposed approach is verified. This paper aims to provide a technical framework and practical experience for the perception and control strategy optimization of VIV in engineering structures or components prone to VIV, such as long-span bridges and suspenders.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF 3D PRINTABLE SELF-SENSING CONCRETE FOR SMART PRECAST CONCRETE STRUCTURES

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ABSTRACT

The emergence of self-sensing cementitious composites (SSCCs) marks a significant advancement in the field of structural health monitoring (SHM). These composites, known for their outstanding sensing performance, offer a cost-effective and compatible alternative to traditional electronic sensors for monitoring the health of concrete structures. SSCCs are not only capable of detecting mechanical forces through their piezoresistive properties but also serve as a repair material, potentially extending the longevity and sustainability of structural components. Despite their promise, the challenge lies in effectively integrating SSCCs into precast structural designs. This study presents a novel approach that harnesses the capabilities of additive manufacturing (AM) to develop 3D printable self-sensing concrete, which can be precisely formulated and strategically incorporated into precast elements for SHM purposes. Utilizing carbon-based conductive fillers, the research identifies optimal mix proportions for self-sensing concrete through comprehensive experimental works. Throughout the study, both monotonic and cyclic axial compressive loads were applied to the concrete specimens to investigate the feasibility of the sensing performance, and subsequent strain changes in the columns were determined using electrical resistivity measurements from the sensing segments. In addition, digital image correlation (DIC) was utilized as a benchmark to confirm the reliability of these self-sensing features. The results of this comprehensive study highlight the transformative potential of integrating functional cementitious materials into precast concrete components through novel construction techniques. It underscores the significant promise of AM technology in propelling sustainable, efficient, and innovative precast concrete construction into the future.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY QUANTIFICATION IN WIND-TUNNEL-INFORMED STOCHASTIC WIND MODELS FOR APPLICATIONS IN STRUCTURAL PERFORMANCE ASSESSMENT

Thays Duarte[1], Srinivasan Arunachalam[2], Arthriya Subgranon[1] and Seymour Spence[2]*

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ABSTRACT

Wind-excited structures are subjected to various sources of uncertainty, which makes it imperative to use probabilistic approaches to reliably assess the performance of such systems, particularly in the context of Performance-Based Wind Engineering. Among the uncertainty sources, considerable variability is observed in wind loads. Appropriate wind load modeling is, therefore, critical for reliable estimation of wind-induced structural responses, especially for dynamically sensitive systems. Wind-tunnel-informed stochastic models have been recently explored as a powerful and efficient method for generating building-specific wind loads. In these models, available short-duration wind tunnel records are typically used to calibrate the spectral eigenvalues and eigenvectors of the target load process, ensuring that aerodynamic phenomena are captured. While data-informed models provide advantages, the accuracy may be limited to the input data, which inevitably contains uncertainties. The quantification of uncertainty in wind loads is, therefore, crucial to ensure the accuracy of simulated wind load processes and the impacts on structural response. To this end, extensive wind tunnel datasets have been collected at the NHERI Boundary Layer Wind Tunnel on a rectangular model for various wind directions and experimental settings, considering suburban terrain. The investigation is conducted considering multiple individual records, where various sources of errors are quantified, including record variability, mode truncation, numerical errors, and the effects of uncertainties in the structural responses. Stochastic wind loads are generated using the newly implemented wind-tunnel-informed model on the WE-UQ application from the SimCenter platform and applied to a dynamically sensitive archetype building model to estimate structural responses. Results provide insight into the impacts of wind load uncertainty on the structural system. The advantages and limitations of the data-informed wind model can also be translated into recommendations for the appropriate use of wind tunnel records in calibrating the stochastic wind model for wind engineering applications.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

QUANTIFICATION AND PROPAGATION OF UNCERTAINTY IN WIND-TUNNEL-INFORMED TRANSLATION MODELS FOR SIMULATION OF NON-GAUSSIAN STOCHASTIC WIND PRESSURES ON BUILDINGS

Thays Duarte[1], Srinivasan Arunachalam[2], Arthriya Subgranon[1] and Seymour Spence[2]*

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ABSTRACT

Appropriate modeling of multivariate stochastic wind processes is essential for the probabilistic performance assessment of wind-excited structures to ensure a safe and reliable design. Modeling the distribution of wind processes is especially important in the tail region, where extreme values usually govern the design of building systems. Stochastic wind models based on the translation process are widely used to generate non-gaussian stationary wind processes that exactly match the target marginal distribution. In particular, such a model can be calibrated directly from wind tunnel records to capture complex aerodynamic phenomena. Despite several advantages, the extent of errors introduced in simulated processes is still unclear due to uncertainties in observed data and model calibration process especially when using typical short-duration records. To investigate this issue, an extensive wind tunnel experiment was conducted on a rectangular model at the NHERI University of Florida Boundary Layer Wind Tunnel, considering multiple wind directions and settings. Errors associated with the wind tunnel record variability, calibration process, model inaccuracy, and mode truncation were evaluated and quantified. Subsequently, a model was proposed to propagate the observed uncertainties to stochastic wind models. Results also provide insights into the requirements of wind tunnel data to ensure adequate estimation of probabilistic information necessary to calibrate stochastic wind models for the accurate simulation of wind processes on bluff bodies.

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN PROCESS UNCERTAINTY ANALYSIS OF STOCHASTIC LACK-OF-FUSION IN LASER POWDER BED FUSION

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ABSTRACT

Laser powder bed fusion (LPBF) is an additive manufacturing technique that has experienced widespread growth in recent years due to many process advantages. However, process-induced defects and their effect on mechanical performance remains a critical issue for parts manufactured using LPBF. Stochastic lack-of-fusion porosity is a critical defect in LPBF that is still not well understood. These defects may occur at build settings that would nominally produce no lack-of-fusion porosity according to widely accepted geometric criteria. This work uses a computational framework which integrates lack-of-fusion porosity into Potts Monte Carlo microstructure simulations to analyze process uncertainties in the volume fraction of stochastic lack-of-fusion pores. The phase-tracking method allows for the simulation of stochastic lack-of-fusion porosity within a microstructure produced by the Potts Monte Carlo technique. The phase-tracking method is initialized by assuming all sites in the simulation domain are unmelted; as the build process is simulated, the sites that coincide with the melt pool volume are designated as melted. The locations of unmelted sites are extracted to reconstruct the morphology and volume fraction of stochastic lack-of-fusion porosity produced by the build parameters. To generate realizations of stochastic lack-of-fusion porosity, melt pool geometry fluctuations were represented in a statistically equivalent manner in the simulation. A spectral matching algorithm was developed to reproduce the fluctuations observed in experimentally imaged scan tracks and coupled with the phase-tracking algorithm to simulate stochastic lack-of-fusion porosity integrated into the Potts Monte Carlo technique. Melt pool geometry fluctuations extracted from the scan tracks represent the effect of all process uncertainties packaged together. Examples of such sources of uncertainty include local laser parameter fluctuations, dynamic absorptivity effects, and spatter generated during the build. The stochastic lack-of-fusion model was calibrated by adjusting the effective absorptivity to match experimental measurements of lack-of-fusion volume fraction. The spectral matching algorithm was then queried and provided to the modified Potts Monte Carlo as input to generate realizations of stochastic lack-of-fusion pores in representative volume element simulations. The effects of the sources of uncertainty on the stochastic lack-of-fusion volume fraction were then analyzed by using Monte Carlo sampling at various processing parameters. This work offers a method to quantify the effects of process uncertainties in laser powder bed fusion on the volume fraction of stochastic lack-of-fusion defects; this is critical to the certification and qualification of parts manufactured via laser powder bed fusion.

Tropical cyclone induced winds, surge-wave, flooding and impacts on infrastructure systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZING COUPLED EXTREME WIND-WAVE LOADS ON OFFSHORE WIND TURBINES USING LARGE EDDY SIMULATIONS

Tianqi Ma[1] *and Chao Sun**[1]

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ABSTRACT

Wind-wave interactions impose wind forcing on wave surface and wave effects on turbulent wind structures, which essentially influences the wind-wave loading on structures. Existing research treats the wind and wave loading separately and ignores their interactions. The present study aims to characterize the turbulent airflow over wave surfaces and wave dynamics under wind forcing and analyze the coupled wind-wave loading on offshore wind turbines. A high-fidelity two-phase model is developed to simulate highly turbulent wind-wave fields based on the open-source program OpenFOAM. A numerical case study is conducted to simulate extreme wind-wave conditions, where coupled wind-wave fields are applied. Simulation result shows that the weighted region of turbulence depends on the relative speed between wind velocity and wave phase speed. The intensity of wave induced turbulences and the height of wave influenced region are affected by the wind velocity and wave heights. Higher wind velocities induce greater turbulence, which can be increased by over 100%. Then the combined wind-wave loading on offshore wind turbines is simulated under operational and extreme conditions. Under operational conditions, the wind-wave coupling effect on the combined loading is minimal. However, under extreme conditions, the coupled wind-wave fields lead to an increase in the average aerodynamic loading and a significant amplification of the fluctuation in the aerodynamic loading. Specifically, the maximum bending moment at both the tower bottom and the monopile bottom experiences an increase of around 6%. Furthermore, the wind-wave coupling effect is evident in the standard deviation of the aerodynamic loading at the tower bottom. The standard deviation of the shear force at the tower bottom increases by up to 45%. Also, the standard deviation of the bending moment at the tower bottom increases by approximately 27%. This study reveals the importance of considering the wind-wave coupling effect under extreme conditions, which provides valuable insights into the planning and design of offshore wind turbines.

Mechanics and modeling of pavement structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECTS OF JET ABLATION AND FUEL CORROSION ON ASPHALT-AGGREGATE INTERFACIAL PROPERTIES AND THEIR MOLECULAR MECHANISMS

Lijun Sun[1], Xingyu Gu[1] and Runhua Zhang[2]*

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ABSTRACT

Airport pavements serve in a more complex environment, including extremely heavy aircraft loads, frequent engine jet ablation, and constant aviation fuel corrosion. The harsh service environment poses significant challenges to the strength and durability of airport asphalt pavements, generating large amounts of foreign objects and debris that threaten the safety of aircraft passengers and assets.

To guide the improvement of asphalt pavement durability in airports, the effects and molecular mechanisms of jet ablation and fuel corrosion on separation failure of the asphalt-aggregate interface were investigated using molecular dynamics (MD) simulations and density functional theory (DFT) method. The tensile separation behaviors of the virgin, aged, and fuel-corroded asphalt-aggregate interfaces were simulated under different loading rates to evaluate their tensile strength and fatigue cracking resistance, and the experimental data were also used to verify the reliability of the simulation results. The molecular mechanisms of jet ablation and fuel corrosion on the separation failure of the asphalt-aggregate interface were then analyzed by calculating the work of adhesion and cohesion, flowability parameters, and intermolecular binding energy. The results show that the aged specimen has higher ultimate tensile strength and fracture energy, but its flexibility and fatigue cracking resistance are significantly reduced. This is because the polar oxygen-containing groups generated during high-temperature aging enhance the intermolecular binding energy of the asphalt, but this also restricts the diffusion of asphalt molecules, resulting in greater frictional resistance and viscosity of asphalt during shear deformation, and thus loss of mobility and self-healing properties. Since the light and medium oils soften and dilute the asphalt and weaken the intermolecular binding energy, fuel corrosion reduces the ultimate tensile strength and fracture energy of the asphalt-aggregate interface system, resulting in insufficient overall strength and load-bearing capacity. The major contributions in this research are summarized as follows:

1) The virgin, aged, and fuel-corroded asphalt-aggregate interface systems are conducted tensile simulations under different strain rates.
2) The effects of jet ablation and fuel corrosion on the interfacial strength and fatigue resistance of asphalt mixtures are quantified.
3) The molecular mechanisms by which jet ablation and fuel corrosion affect the properties of asphalt-aggregate interface systems are investigated through MD simulations and the DFT method.

In future works, we can further set up more comprehensive simulation conditions, including more aggregate types, larger model sizes, and loading rates closer to those of macroscopic tests to reduce the discrepancy between simulation results and experimental data.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE NUMERICAL MODELING OF MICROSTRUCTURAL DAMAGE AND TENSILE STRENGTH OF UHPC

Yanmo Weng[1] and Lizhi Sun[1]*

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ABSTRACT

We developed a micromechanics-based multiscale method to investigate the tensile behavior for ultra-high performance concrete (UHPC). The finite element approach was coupled with cohesive zone model based on the UHPC microstructure obtained from micro-CT techniques. To develop a multiscale modeling model, two kinds of cohesive elements were embedded in the micromechanics model to explain the degradation of fracture properties. The microcrack growth rates were discussed to further analyze the effective strength of UHPC. A satisfactory agreement was achieved between the simulation results and the experimental data from the direct tensile tests associated with curing age and freeze-thaw cycles. As demonstrated, the proposed model integrated with the X-ray CT techniques can be used as an effective and reliable numerical simulation approach to capture the relation of microstructural damage and overall tensile behavior of UHPC materials.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MEASURING TORSIONAL DISPLACEMENT USING MULTI-VISION SYNCHRONIZATION IN SHAKE TABLE TESTS

Mohammad Vasef[1], Peng "Patrick" Sun[1] and Kevin Mackie[1]*

[1]University of Central Florida

ABSTRACT

Measuring both torsional and translational displacement is crucial for system identification and modal analysis in three-dimensional (3D) building models, especially when torsional modes are within the first few modes of vibration. However, conventional methods, such as accelerometers and linear variable differential transformers (LVDTs), need rectification (e.g., double integration and drift offset for accelerometers, string length rectification in specific directions for LVDTs) to accurately measure the torsional displacement. Vision-based methods have the potential for out-of-plane displacement monitoring using multiple perspectives. This work is the first shake table study measuring torsional displacements using a synchronized, multi-vision system. In this study, a multi-vision-based approach is proposed to measure 3D dynamic structural displacements (e.g., torsional), and the effect of different synchronization methods is studied with affordable cameras. Finite element simulation on a 3D aluminum frame is conducted to design small-scale shake table tests (e.g., stiffness, mass, excitation) to induce torsional displacements from unidirectional excitation, which are used to evaluate the proposed monitoring method. Fiducial markers (e.g., AprilTags) and conventional sensors (e.g., accelerometers, potentiometers) are deployed on each story of the frame. A camera system is developed with four perspectives to monitor displacements with three in front and one on top of the shake table. The measurement results show improved accuracy with reduced error over raw potentiometer measurement. Useful guidelines are also provided on the synchronization for affordable camera system and on extrinsic camera calibration in practice.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NOVEL METHOD FOR TOPOLOGY OPTIMIZATION OF EIGENFREQUENCIES OF STRUCTURES WITH SINGLE/REPEATED EIGENVALUES

Shiyao Sun[1] and Kapil Khandelwal[1]*

[1]University of Notre Dame

ABSTRACT

This study focuses on the topology optimization of vibrational frequencies of structures with both single and repeated eigen-frequencies. In the context of finite element analyses, such problems lead to generalized eigenvalue problems, and the goal is to optimize suitably constructed functions of eigenvalues/frequencies. In gradient-based optimization, the main challenge in topology optimization of these problems arises from the non-differentiability of eigenvalues when they are repeated. In the past, this issue was addressed: (a) by using directional derivatives, but such an approach led to a more involved optimization procedure, or (b) by introducing artificial constraints in problem formulation to ensure that the eigenvalues remain simple, which will lead to suboptimal design in cases where the final optimized design is expected to have repeated eigenvalues. To address the non-differentiability of repeated eigenvalues, this work proposes novel formulations that employ symmetric differentiable polynomials of eigenvalues for eigenvalue optimization. In particular, a mean-clustering approach is employed together with bound variables to obtain optimization formulations for maximizing target frequencies and bandgaps. The differentiability of the employed symmetric polynomials is ensured by incorporating all the needed repeated eigenvalue clusters. The proposed formulations are used to optimize vibrational properties – eigen-frequencies and bandgaps – of 2-D and 3-D solids as well as plate structures with single and multi-material phases. Numerical results demonstrate the efficacy of the proposed approaches in obtaining optimized designs with both simple and repeated eigenvalues.

Computational geomechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEISMIC DAMAGE ANALYSIS OF UNDERGROUND FRAME STRUCTURES WITH PERIDYNAMICS

Wei Sun[1] and Enpeng Lin[1]*

[1]Sun Yat-Sen University

ABSTRACT

Strong earthquake poses a significant threat to the structural integrity of underground frame structures. This paper presents an innovative seismic simulation analysis method for underground frame structures, integrating the response displacement method (RDM) with peridynamics (PD). In the numerical model, peridynamics (PD) is employed to simulate underground structures, effectively capturing the initiation and propagation of cracks within the structures. Seismic effects are introduced through RDM, applying soil shear force and structural inertial forces to the structure. The efficacy of the proposed numerical methods is assessed through comparison with dynamic centrifuge tests. The nonlinear collapse and failure mechanism of the Daikai Subway station during the 1995 Kobe earthquake are elucidated. Numerical results demonstrate that this approach facilitates the replication of damage patterns in underground frame structures subjected to seismic effects, with an explicit representation of cracks. A parametric study is conducted to explore the influence of key factors on the damage patterns of underground frame structures.

Industry challenges in engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHALLENGES IN FATIGUE LIFE PREDICTION OF EXPANSION JOINTS IN PETROCHEMICAL INDUSTRY USING COUPLING-ELEMENT-EMBEDDED FINITE ELEMENT APPROACH

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[1]SINOPEC Engineering Incorporation

ABSTRACT

Expansion joints are widely used in petrochemical pipelines under high temperature and corrosive environments. The complex shape of expansion joints enables its capability to sustain tensile and compressive loads, compensate pipe displacement, and absorb mechanical vibration. However, the constant displacement and dynamic load acting on expansion joints can lead to fatigue failure, which significantly increases the risk of pipeline leakage in petrochemical plants. Thus, the fatigue life prediction of expansion joints based on computational modeling is necessary.

Stress analysis of petrochemical pipelines is commonly conducted using commercial FEA software, such as CAESAR II and AutoPIPE, which take the strategy to simulate the pipe and all essential components using one-dimensional beam element. This geometric simplification fails to capture the complex shape of expansion joints, which does affect the precision of fatigue life prediction. Therefore, a modified finite element method for coupling one-dimensional and three-dimensional elements is highly demanding. Instead of using three-dimensional elements globally, a mixed-dimensional model can significantly reduce the total number of degrees of freedom, which maintains high computational efficiency. In this work, the major challenge is to figure out an algorithm to connect elements with different dimensions, which involves mesh and geometry processing together with an adaptation of boundary representation.

MITIGATING VORTEX-INDUCED VIBRATION CHALLENGES IN LONG-SPAN BRIDGES: A COMPREHENSIVE STUDY OF CHONGQI BRIDGE

Zhen Sun[1] and Xuyong Ying[2]*

[1]*Southeast University*
[2]*Jiangsu Transportation Institute*

ABSTRACT

This study addresses the application of TMD to mitigate excessive vibration and evaluation of the TMD performance using machine learning-based method. Chongqi Bridge, a crucial link spanning the Yangtze River between Chongming City in Shanghai and Qidong City in Jiangsu, faced challenges marked by vortex-induced vibration (VIV) during construction. Comprising twin six-span structures, each 16 m wide and 944 m long, a vibration test and implementation of the eigen-system realization algorithm (ERA) were carried out to discern mode properties. Wind tunnel tests unveiled potential VIV in the first vertical mode, prompting the installation of tuned mass dampers (TMDs) in the four middle spans to counter significant vibrations.

A Structural Health Monitoring (SHM) system, equipped with anemometers, accelerometers, and displacement transducers, was deployed on both the bridge and the TMDs [1]. Amid Typhoon Chan-hom in July 2015, wind characteristics were computed using monitoring data, evaluating the bridge and TMDs' responses [2].

Recognizing the imperative of comprehending TMDs' long-term performance, an innovative machine learning (ML)-based approach emerged to assess their effectiveness subject to strong winds. Leveraging four ML techniques—artificial neural network (ANN), decision tree (DT), random forest (RF), and gradient boosting regression tree (GBRT)—SHM data served as training input. Wind properties and temperature parameters became key inputs, with TMD accelerations as outputs. Employing the Shapley Additive exPlanations (SHAP) method [3], influential factors on TMD performance were identified, revealing wind velocity and temperature as pivotal parameters.

This strategy emerged as a dependable tool for evaluating TMD effectiveness. As bridges commonly employ multiple TMDs to prevent vibrations, this method stands as an effective means to assess and cross-verify sustained TMD stability against varying environmental challenges.

Reference

[1] Zhen Sun; Zilong Zou; Yufeng Zhang. Utilization of structural health monitoring in long-span bridges: Case studies, Structural Control & Health Monitoring, 2017, 24(10): e1979.
[2] Zhen Sun; Zilong Zou; Xuyong Ying; Xianqi Li. Tuned Mass Dampers for Wind-Induced Vibration Control of Chongqi Bridge, Journal of Bridge Engineering, 2019, 25(1): 05019014.
[3] Z Sun; DC Feng; S Mangalathu; WJ Wang; D Su. Effectiveness assessment of TMDs in bridges under strong winds incorporating machine learning techniques. Journal of Performance of Constructed Facilities. 2022, 36(5): 04022036.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RELIABILITY-BASED OPTIMIZATION OF MINIMUM SHEAR REINFORCEMENT IN PRESTRESSED CONCRETE BEAMS VIA RESERVE SHEAR STRENGTH INDEX AND BAYESIAN REGRESSION

Wonsuh Sung[1], Nikhil Potnuru[1], Suhaib Alfaris[2], Stephanie Paal[1], Maria Koliou[1], Petros Sideris[1], Mary Beth Hueste[1], Anna Birely[1] and Stefan Hurlebaus[1]*

[1]*Texas A&M University*
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ABSTRACT

This study introduces a novel methodology for optimizing minimum shear reinforcement in prestressed concrete (PC) beams, emphasizing reliability analysis via the Reserve Shear Strength (RSS) Index. The RSS Index reflects the ratio of shear force at failure over shear force at the onset of diagonal cracking, showcasing an enhanced structural capacity against escalating shear forces. The 2015 ACI-DAfStb database, incorporating ACI 445-D Committee and ACI-DAfStb Committee databases, is herein augmented with additional experimental datasets for a comprehensive analysis. Influential factors impacting shear capacity, such as beam depth, shear span-to-depth ratio, longitudinal reinforcement ratio, concrete tensile strength, prestressing level, and shear reinforcement properties, are systematically identified. Subsequently, Bayesian regression optimizes equations predicting shear forces at critical points using the assembled dataset. This approach addresses data limitations and uncertainties through probabilistic distributions for each coefficient of the strength prediction equations. Using Monte-Carlo simulations, these equations enable reliability analysis to determine the optimal value for the RSS index, and thus, the optimal minimum required shear reinforcement. Our ongoing work has shown that the typical RSS value of 1.3 yields minimum shear reinforcement estimates that are lower than those stipulated by existing ACI 318 and AASHTO LRFD standards. This preliminary observation suggests the potential for optimizing shear reinforcement design, with significant implications for enhancing structural engineering practices and fostering the development of more efficient and economical prestressed concrete structures.

A new horizon - Quantum computing and quantum materials (by invitation only)
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPUTING SPARSE APPROXIMATE PRECONDITIONERS FOR TOPOLOGY OPTIMIZATION ON QUANTUM ANNEALING MACHINES

Krishnan Suresh[*1]

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ABSTRACT

Topology optimization entails repeatedly solving finite-element-based linear systems of equations. These linear systems are often poorly conditioned since the underlying topological density field can vary by ten orders of magnitude. This talk will explore using quantum annealing machines for computing sparse-approximate-inverse (SPAI) as effective pre-conditioners for these linear systems [1]. Furthermore, the pre-conditioners can be computed rapidly by exploiting the uniform structured mesh typically used in topology optimization.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DOUBLE-NETWORK-INSPIRED WOVEN METAMATERIALS

James Surjadi[1], Bastien Aymon[1], Molly Carton[1] and Carlos Portela[1]*

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ABSTRACT

The development of mechanical metamaterials has predominantly focused on attaining high stiffness and strength while maintaining low densities, ranging from classical periodic truss lattices to plate and shell lattices that can achieve stiffness and strength close to theoretical limits. However, the presence of sharp joints or nodes often induce stress concentration issues that compromise ductility or stretchability. On the contrary, recently reported stretchable metamaterials, exemplified by helical and woven lattices, mark a significant departure from the conventional paradigm. Nevertheless, these stretchable designs often incur a substantial reduction in stiffness, amounting to multiple orders of magnitude compared to traditional high-stiffness lattices. This pronounced trade-off, which is also commonly observed in virtually all existing material systems, considerably constrains the energy dissipation capabilities of metamaterials.

Here, by drawing inspiration from double-network hydrogel systems, we propose a route to fabricate metamaterials with extreme combinations of stiffness and stretchability. This double-network-inspired (DNI) metamaterials integrates both monolithic truss and woven architectures to act as stiff and compliant networks, respectively. In situ micro-tension experiments showcase a simultaneous high stiffness and stretchability (more than 10 times higher compared to its constituent material), resulting in a multi-fold increase in energy dissipation compared to their counterparts. By employing non-linear finite element modeling, we establish that the enhanced energy dissipation can be linked to the increased entanglements between the monolithic and woven components, augmenting frictional dissipation. Intriguingly, the introduction of internally distributed defects further amplifies energy dissipation by delocalizing failure, a departure from the typical scenario where defects often result in the degradation of mechanical properties. Our work not only provides a strategy for mitigating the stiffness-stretchability trade-off in existing metamaterials but also charts a route for creating new classes of metamaterials inspired by polymer networks.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTIPHYSICS DEGRADATION MODELING OF ENERGY STORAGE MATERIALS VIA RKPM WITH A NEURAL NETWORK-ENHANCEMENT

Kristen Susuki[1], Jeffery Allen[2] and Jiun-Shyan Chen[1]*

[1]University of California, San Diego
[2]National Renewable Energy Laboratory

ABSTRACT

In energy storage materials, strong electrochemical-mechanical coupling and highly anisotropic material properties contribute to the formation and propagation of micro-cracking during charge/discharge cycling, resulting in reduced performance and service life. A coupled electro-chemo-mechanical reproducing kernel particle method (RKPM) formulation is developed, and a patch-test is formulated to certify optimal convergence of the proposed RKPM method for the coupled physics system. With microstructural images supplied by the National Renewable Energy Laboratory (NREL), pixel-based model construction by RKPM is then used to represent the complex material microstructures for modeling the coupled physics of these systems. Further, a neural network-enhanced reproducing kernel particle method (NN-RKPM) [1, 2] is introduced to effectively model damage and crack propagation in the material microstructures; the location, orientation, and solution transition near a localization are automatically captured by superimposed block-level NN optimizations. This NN enrichment approach allows for effective modeling of localizations via a fixed background discretization, relieving tedious efforts for adaptive refinement in traditional mesh-based methods. Applications to the heterogeneous microstructures of Li-ion battery cathodes will be presented to demonstrate the effectiveness of the proposed methods.

Reference:
[1] Baek, J., Chen, J. S., Susuki, K., “Neural Network enhanced Reproducing Kernel Particle Method for Modeling Localizations,” International Journal for Numerical Methods in Engineering, Vol. 123, pp 4422-4454, https://doi.org/10.1002/nme.7040, 2022.
[2] Baek, J., Chen, J. S., “A Neural Network-Based Enrichment of Reproducing Kernel Approximation for Modeling Brittle Fracture”, Computer Methods in Applied Mechanics and Engineering Vol. 410, 116590, 2024.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIBRATION PROBLEMS IN THE COUPLED THEORY THERMOELASTIC NANOMATERIALS WITH TRIPLE POROSITY

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ABSTRACT

The mathematical models of nanoporous materials represent a new possibility for the study of important problems of engineering and technology. Indeed, nanomaterials with multi-porosity structure have wide applications in civil and geoengineering, technology, medicine and biology. Obviously, to determine the mechanical properties of materials with such a structure, it is very important to construct appropriate mathematical models.

In the present talk, the coupled linear theory of thermoelasticity for nanomaterials with triple porosity is considered in which the coupled effect of the Darcy's law and the volume fraction concept of pore network is proposed. The fundamental solution of the system of steady vibration equations is constructed explicitly by elementary functions. Green’s identities are obtained and the uniqueness theorems for the classical solutions of the basic internal and external BVPs of the steady vibrations are proved. The surface and volume potentials are constructed and the basic properties of these potentials are established. The BVPs are reduced to the equivalent always solvable singular integral equations for which Noether’s theorems are valid. Finally, the existence theorems for classical solutions of the aforementioned BVPs are proved by means of the potential method and the theory of singular integral equations.

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Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE CONVEXITY OF PHASE-FIELD FRACTURE FORMULATIONS: ANALYTICAL STUDY AND COMPARISON OF VARIOUS DEGRADATION FUNCTIONS

Lampros Svolos[1], JeeYeon Plohr[2], Gianmarco Manzini[2] and Hashem Mourad[2]*

[1]University of Vermont

[2]Los Alamos National Laboratory

ABSTRACT

In recent decades, the phase-field fracture (PFF) method has received significant attention due to its ability to capture complex fracture patterns. Crack propagation and branching can be modeled by minimizing a total energy functional, which is regularized using an auxiliary phase field. Despite the promising results demonstrated by the PFF method across various applications, computational challenges are mainly associated with the non-convexity of the total energy functional with respect to the combined unknown (phase field and displacement) fields. As a result, understanding the effects of their coupling on convexity is crucial to address frequently encountered hurdles in fracture modeling, involving inefficient solvers.

In this presentation, we establish convexity criteria for a wide class of PFF formulations. Within this formulation class, the second variation of the total energy functional is expressed in terms of Hessian matrices, evaluated at individual material points. Based on the selection of geometric crack functions and degradation functions, we classify the formulations into three categories and conduct analytical studies for each one separately. To determine the sign of the second variation, we derive inequalities that hold at material points when the Hessian matrix is locally positive semi-definite. These inequalities serve as objective criteria for comparing degradation functions. The applicability of the proposed convexity criteria is demonstrated by solving a one-dimensional problem with the aid of a monolithic numerical integration scheme.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADAPTIVE CAMBER PRECAST CONCRETE GIRDER FOR DEFLECTION MITIGATION

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ABSTRACT

Camber in precast and prestressed concrete is currently designed using best practices in structural engineering and subject to climate and loading uncertainties. Applying new technology of adaptive structures, large shape change in response to load, to precast concrete bridge girders would pioneer a new innovative field of research and design. This work is to build, analyze, and validate an adaptive precast girder system that will use expanding anchors to camber the compression face of the girder to counteract imposed loads. By providing on-demand camber, sizing of the precast member for deflection criteria can be reduced. Through this form of topology optimization, reduction in concrete volume will increase the sustainability of the structural system. Motivation for this work is twofold: topology optimization and long-term deflection control for transforming precast concrete research. A bridge girder that contains the science of adding camber when loads are applied can reduce girder depth for stiffness requirements, optimizing material utilized as a sustainable solution in the light of climate change. Anchors inserted into slots along the top face of the girder expand longitudinally in the compression zone of the girder when vertical load is applied. This causes the compression face to elongate, thus creating camber. The analytical demand for surplus compression for camber is calculated for a sample concrete beam and deployable anchors are tested outside of the concrete medium to determine their individual capacity for shape change. Finally, a small specimen is experimentally vertically loaded while anchors are undeployed and deployed to assess change in deflection.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL SIMULATION OF THE LATERAL BEHAVIOR OF 3D-PRINTED HEMPCRETE (3DPH) WALLS

Mohammad Syed[1], Sumedh Sharma[1], Tal Mizrachi[1], Mohammad Aghajani Delavar[1], Maria Koliou[1] and Petros Sideris[1]*

[1]Texas A&M University

ABSTRACT

Three-dimensional (3D) printed buildings are being increasingly seen as the future of sustainable building construction. Construction 3D printing has the potential to create affordable houses of uniform quality in significantly lesser time than other conventional construction techniques. Furthermore, 3D printing of structures using hempcrete, a net carbon-negative material, can provide a building technique that combines the advantages of automated construction with those of less carbon-intensive building materials, for greater sustainability.

This study characterizes the lateral behavior of 3D-printed hempcrete (3DPH) walls using finite element modeling. The walls considered herein are representative units of larger wall assemblies (of single-story houses) designed for resisting lateral loads from earthquakes and wind, in addition to gravity loads. A finite element modeling methodology is developed, and in lack of experimental data from 3DPH walls, is validated using test data on 3D-printed concrete walls executed by some of the co-authors, which are from the same family of building techniques as 3DPH walls. Numerical models of 3DPH wall units are built, and static pushover analyses are performed to study their in-plane behavior, which includes the lateral strength characteristics, damage evolution, and force-transfer mechanisms. The effects of design parameters – axial load level and aspect ratios – on their performances are also studied. Damage assessment of the assemblies is carried out to identify different potential damage states and corresponding limit states, largely informed by the literature on damage studies of similar systems, to be used subsequently for fragility analysis of 3DPH walls.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPLORING THE ROLE OF INFORMATION FIDELITY WHEN CONSTRUCTING REDUCED-ORDER MODELS (ROMS) FOR REGIONAL RISK ASSESSMENT SEISMIC APPLICATIONS

Parisa Toofani Movaghar[1], Sang-ri Yi[2], Alexandros Taflanidis[1] and Carmine Galasso[3]*

[1]University of Notre Dame
[2]University of California, Berkeley
[3]University College London

ABSTRACT

The increasing interest in the past decade in regional seismic risk applications has revealed new requirements in terms of robustness and computational efficiency for the numerical frameworks adopted to estimate structural response within such contexts. These requirements pertain to both the computational burden for performing large scale (with thousands of buildings) response history analysis for nonlinear structures, as well as to the fidelity of the information needed to establish structural models that adequately describe the linear and nonlinear response characteristics for the examined building portfolio. In parallel, reduced order models (ROMs) have emerged as a popular alternative to high-fidelity Finite Element Models (FEMs), dramatically reducing computational burden for structural simulations. For regional risk assessment ROMs can be used to characterize the building archetypes within specific regions reflecting building properties impacting linear and hysteretic behavior, such as fundamental period and yielding drift ratio, respectively. The type and fidelity of information (i.e., basic building inventory information or detailed information considering the structure's typology and material) incorporated in the ROM development in this context has an important influence on the regional risk assessment results. This study examines the role of information fidelity in constructing ROMs. This is accomplished by considering differences, hierarchy, and information classes for archetype moment resisting frame structures using a ROM formulation. Such an influence is quantified by the comparison of the predictions between the different ROM classes by setting the ROM parameters as uncertain with different degrees of variability reflecting the type and fidelity of information available. Parametric and global sensitivity analysis techniques are developed to examine the underlying trends and an efficient framework is established to accommodate comprehensive comparisons. Furthermore, all comparisons are established for different hazard exposure levels (different seismic intensities), allowing a further disaggregation of the observed trends to the underlying hazard intensity. Results reveal the importance of information fidelity when ROMs are adopted as computationally efficient low-fidelity models within regional risk assessment applications and thought the sensitivity trends help pinpoint the exact ROM characteristics for which this importance is greater.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCES IN SPATIO-TEMPORAL STORM SURGE PREDICTION USING METAMODELS

WoongHee Jung[1] and Alexandros Taflanidis[1]*

[1]University of Notre Dame

ABSTRACT

The prediction of storm surge hazards has emerged as a top priority in discussions about coastal community resilience. This importance has increased in the past few years due to the recent highly active hurricane seasons and the growing concerns associated with climate change, whose impacts include sea-level rise and increased intensity and recurrence rates of storms. One of the key advances in this domain has been the development of high-fidelity numerical models to establish accurate predictions for the expected surge for a given hurricane event. To reduce the computational burden of using such models in regional coastal hazard studies or real-time surge forecast applications (during landfalling storms), the use of surrogate modeling (also known as metamodeling) techniques has emerged as a popular strategy. The established metamodels need to provide spatio-temporal predictions for the surge evolution (over time) across a large geographic domain (the storm impact), as it is essential to understand the interaction of the surge with other flood components and ultimately assess the compound flood risk accurately. The standard formulation for developing metamodels in this context (independent of the specific metamodeling approach adopted) involves: (a) an imputation step to accommodate missing data associated with instances nodes remained or became dry during the storm evolution and (b) a dimensionality reduction step for projection to a latent space to improve computational efficiency for metamodel calibration and prediction. This paper proposes advances across both these aspects. For the data imputation, probabilistic principal component analysis (PPCA), a purely data-driven approach, is adopted and applied to surge responses over the locations in the geographical domain of interest across different time steps and storms simultaneously. Performing PPCA across all available storms (instead of separately for each storm) improves imputation accuracy, yielding smooth time series and maintaining spatial correlation of the surge predictions. As a dimensionality reduction technique, higher-order singular value decomposition (HOSVD) is applied separately across the spatial and temporal dimensions of the database. HOSVD improves prediction accuracy over alternative approaches that do not separate these two dimensions. The combination of PPCA within HOSVD is also examined to integrate the data imputation within the latent variable projection. In the calibration of the metamodel, latent responses are grouped based on their importance, and calibration is performed separately for each group. The performance of the metamodel under different grouping strategies is discussed in the case study.

A MACHINE LEARNING-BASED SURROGATE MODELING APPROACH FOR SEISMIC RESPONSE ANALYSIS OF SOIL-STRUCTURE SYSTEMS

Hamid Taghavi Ganji[1] and Elnaz Seylabi[1]*

[1]University of Nevada Reno

ABSTRACT

This research proposes a machine learning-based surrogate modeling approach for accurate yet efficient seismic response analysis of soil-structure systems under uncertainty. The proposed model is built using long short-term memory recurrent neural networks suitable for predicting sequential time series. The proposed model is designed to accommodate both the time history of the incident plane waves and the system properties (e.g., angle of incidence and soil properties) as sources of uncertainties. Additionally, it is designed to employ short-duration synthetic time histories for training instead of earthquake records to ensure efficiency. We test the performance of the proposed surrogate modeling approach in several configurations, including performing Monte Carlo-based forward uncertainty quantification and sensitivity analysis. All studied cases suggest promising accuracy of the proposed surrogate modeling approach and computational efficacy reaching more than two orders of magnitude.

ENHANCING DATA EFFICIENCY AND ACCURACY IN FINITE ELEMENT ANALYSIS USING MULTI-FIDELITY GRAPH NEURAL NETWORKS

Mehdi Taghizadeh[1] and Negin Alemazkoor[1]*

[1]University of Virginia

ABSTRACT

Engineering models often rely on partial differential equations (PDEs), which are usually solved using finite element analysis (FEA). However, as models grow in complexity, these conventional methods can be prohibitively resource-intensive. Machine learning, and specifically convolutional neural networks (CNNs), have been proposed as alternatives for solving PDEs. Yet, CNNs face difficulties in handling irregular geometries. This challenge has led to the adoption of graph neural networks (GNNs), which are more adept at representing complex shapes. The primary drawback of GNNs, though, is their dependence on large datasets for accurate modeling. Our study introduces a new approach that integrates multi-fidelity modeling with GNNs, effectively representing complex geometries while reducing the need for extensive training datasets. The approach begins with a low-fidelity GNN model, which uses data from coarse meshes for initial approximations. The process is then augmented by a high-fidelity model that utilizes data from fine meshes, involving intricate details and complex graph interactions for more accurate approximations. This two-tiered method strikes a balance between computational efficiency and accuracy, addressing a key challenge in FEA. Our approach also features an advanced GNN framework tailored for mesh-based simulations. In this framework, FEA meshes are represented as graphs, where nodes represent important geometric points with physical attributes like boundary conditions, and edges illustrate interaction and connectivity among these nodes. The GNN's architecture includes an encoder for converting meshes into graphs, a processor updating mesh embeddings via message-passing, and a decoder interpreting latent node features for accurate approximations. The effectiveness of our model is demonstrated through various solid mechanics examples.

Integration of physics-based models with data for identification, monitoring, estimation, and uncertainty quantification

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SOIL-STRUCTURE SYSTEM IDENTIFICATION USING BAYESIAN FINITE ELEMENT MODEL UPDATING

Abdelrahman Taha[1] and Hamed Ebrahimian[1]*

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ABSTRACT

Given the potentially significant impact of soil-structure interaction (SSI) on the seismic response of building structures, numerous analytical solutions, also known as impedance functions, have been introduced in the literature for SSI analysis. These solutions, however, are based on certain idealizations and assumptions about the soil-structure system behavior that can be violated in the real world, rendering the accuracy of these solutions questionable. To address this issue, system identification – using a Bayesian finite element model updating technique – is adopted as a powerful tool facilitating the estimation of impedance functions from the recorded response of real-life buildings to vibration tests or seismic motions. The analytical solutions are then to be benchmarked against their estimated counterparts. In this study, the proposed system identification framework is applied to a test structure located in Garner Valley, California using its recorded response during a forced-vibration test. The obtained estimation results are compared to the existing analytical solution, and the observed discrepancies are discussed.

A MACHINE LEARNING FRAMEWORK FOR PREDICTING CONCRETE PROPERTIES

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ABSTRACT

Concrete is a complex heterogenous material, hence, the ability to estimate the effective properties of the overall mixture is not straight forward. Traditional experimental design methods are generally based on a trial and error approach. Moreover, these methods aim at providing acceptable solutions rather than optimal ones. Experimental-based methods have shown practical acceptability of the final product properties and is thought to be feasible when there is only one objective to be optimized. However, in most cases, multiple objectives (e.g. strength, slump, durability) need to be optimized simultaneously. This will cause an exponential increase in the number of concrete samples to be prepared. Additionally, the current empirical equations presented in the codes and standards for estimating properties such as compressive strength are based on tests of concrete prepared without supplementary cementitious materials SCM (fly ash, slag, … etc.). Hence, a different approach should be followed for more accurate predictions. Accurate predictions would allow a concrete producer to design and proportion “optimal” mixtures that minimize material waste, cost and negative environmental effects, while still meeting a given design requirement. In this research, machine learning (ML) models will be developed for reliable prediction of concretes with SCM. We start by enhancing the robustness of the current ML models by incorporating physics-based information for predicting compressive strength and yield stress. For concrete, these physics-based models do not exist for the whole mixture design problem; rather, they exist for certain sub-problems associated with concrete properties. For instance, some physics-based models predict aggregate packing density as a function of particle size distribution. In this research, a novel framework for training neural network architectures using the knowledge in physics-based equations using physics guided neural network models (PGNN) is presented. This model ensures the learning of physically consistent solutions regarding the predicted properties. We adopt these models for predicting compressive strength and yield stress. Compared to basic models with no physical information, better accuracy is obtained. Another proposed model is what we call a generalized model for predicting concrete properties prepared with new additive materials (i.e. not used in the training data set). Such a model results in promising outcomes compared to traditional models that cannot accommodate new materials. This model will also overcome the drawbacks of the already existing ML models as they don’t count for the physical and chemical properties of the constituent materials.

PREDICTING EARTHQUAKE FAULT DYNAMICS AND PARAMETRIC IDENTIFICATION THROUGH PHYSICS-INFORMED NEURAL NETWORKS

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ABSTRACT

The study of earthquake mechanics has traditionally relied on analytical and numerical methods, which often encounter challenges in capturing the complex, nonlinear behavior of fault systems. Despite advances in our comprehension of fault structure and plate tectonics, it remains crucial to align real-world data with the mechanics. Recently, machine learning has emerged as an alternative technique for addressing physics-related problems by integrating data and physics. In this study, we employ a Physics-Informed Neural Network (PINN) to investigate emergent dynamics in earthquake fault motion using the slip law formulation of the nonlinear rate-and-state friction law attached to the Burridge-Knopoff spring-block model. PINN enables us to predict the slip evolution of a spring-block model coupled with the rate-and-state friction law within the context of the forward problem. Furthermore, we integrate PINN with measurements to estimate a constant frictional parameter in the friction law via time-independent inverse PINN and track the evolution of friction over time through time-dependent inverse PINN. Lastly, we propose a mixed scheme of time-dependent and time-independent inverse PINN to determine the velocity-weakening and -strengthening regime of the fault. Our findings suggest that PINNs can successfully simulate slip evolution with no measurements applied. For the inverse problem, we successfully reveal the fault's parameters given the available measured data. PINN offers an innovative approach to comprehend and predict fault dynamics, providing a robust technique for parametric identification.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELLING TUNED LIQUID DAMPERS USING SMOOTHED PARTICLE HYDRODYNAMICS

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ABSTRACT

Flexible, lightly damped buildings can be vulnerable to wind induced motions that can lead to occupant discomfort, increased structural member forces, building service interruptions, and building envelope damage. A Tuned Liquid Damper (TLD) can be installed to significantly reduce the amplitude of resonant vibrations, resulting in lower structural loads, substantial cost savings and enhanced building performance. A TLD can be relatively inexpensive to install and operate compared to other types of dynamic vibration absorbers and can also serve as a source of water for a building's fire suppression system. One restriction to installing a TLD in a building is obtaining the necessary space for the tank. Building owners and developers might be hesitant to dedicate space solely for a TLD near the top of a building where real estate values are highest. Unique TLD tank shapes to optimize TLD performance and utilizing the TLD as part of a fire suppression system can aid in reducing dedicated space requirements. Smoothed Particle Hydrodynamics (SPH) has been applied to model complex free surface problems and fluid structure interaction. SPH has also been successfully used to model TLDs using both incompressible (ISPH) and weakly compressible (WCSPH) formulations. Although linear and multi-modal models have been utilized to investigate complex tank geometries, they are often limited to a certain response amplitude. Various boundary condition implementation techniques have been investigated in SPH to model the tank walls, internal voids and damping screens that provide supplementary energy dissipation within the TLD. Results for different TLD tank bottom geometries using SPH will be presented. Existing SPH code has been modified, with a particular focus on updated boundary conditions to accommodate sloped and curved bottom tanks. The SPH model can be used to model flat, sloped, parabolic, and circular bottom tanks under large excitation amplitudes corresponding to extreme wind events. In addition, a unique tank with a perforated floor, modelled using a macroscopic model to capture the effect of the perforations is also presented. The perforated floor is also modelled microscopically, using rigid boundary particles, to validate the proposed macroscopic model. This unique perforated tank floor arrangement may allow the TLD to serve as both a vibration absorber and as part of a fire suppression system. Its performance as a vibration absorber is compared to that of a traditional TLD under a range of response level amplitudes.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FRAMEWORK TO MITIGATE WIND-INTENSIFIED WILDFIRE INCIDENTS CAUSED BY FAILURES IN ELECTRIC POWER SYSTEM COMPONENTS

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ABSTRACT

Since 1983, the frequency of wildfire incidents in the US has quadrupled. Wildfires could be triggered by lightning or volcanic eruptions, human interventions, or ignitions caused by power system failures. In Southern California, more than 10% of all burnt areas are due to Wildfires triggered by Santa Ana winds causing failures in power system equipment. Santa Ana winds are known for hot and dry seasonal weather effects that cause failures in power system equipment and dry vegetation providing fuel for wildfires. For example, in October 2007, Southern California experienced a strong Santa Ana wind event which led to 20 significant fires that burned around 500,000 acres. This became the third most destructive wildfire in California history. Most failures in power system equipment that led to wildfires were due to tree-related faults. The existing literature does not provide any model to predict the likelihood of wildfire ignitions due to fallen trees.

To fill in this knowledge gap, this study develops a framework that uses historical weather data to estimate Seasonal Exceedance Probability (SEP) for Santa Ana winds using exponential distribution. Moreover, logistic regression is used to account for uncertainties in wind intensity, tree and power line conductors' characteristics, and vegetation to estimate the likelihood of wildfire ignition. For this purpose, first, a physics-based model for trees is generated to account for stem breakage and uproot modes of failure. Second, using geometric relations, based on distances between trees, poles, and conductors, elevation of conductors, and wind angle, it is estimated if the tree would hit the conductors. Third, the impact load that is applied from fallen trees to conductors is estimated by modeling fallen trees and conductors in LS-Dyna to estimate conductor breakage. Fourth, a data-driven model for vegetation ignition is used to determine binary events of ignition/no-ignition, which will be used in logistic regression to determine the probability of wildfire ignition. Subsequently, the ignition model provided in this study is integrated with the seasonal wind model to determine the seasonal and annual expected number of wildfire ignitions for a real distribution line in a forested area in Southern California. The preliminary results show that depending on the density of trees, the distance between trees and power lines, and the intensity of tree-cutting programs, wildfire incidents can be substantially reduced. Therefore, this study provides a critical framework for policymakers and electric utility managers to prioritize risk management strategies and safeguard wildfire-prone communities.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SINGULAR VALUE DECOMPOSITION PROBLEMS IN STRUCTURAL DYNAMICS: A QUANTUM COMPUTING SOLUTION TREATMENT

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ABSTRACT

A quantum computing approach is developed for solving singular value decomposition (SVD) problems of relevance to structural dynamics applications, such as vibration control of structures and multi-body system dynamics [1-2]. Specifically, various algorithms have been developed for treating, numerically, SVD problems in conjunction with classical computers. However, the associated computational complexity increases as a power function of the dimensions of the involved matrix [3]. Clearly, the cost becomes prohibitive for large-scale finite element models of complex structural systems. To circumvent the above challenge, the potential of quantum computers for performing complex tasks vastly more efficiently than classical computers is explored herein. Specifically, a variational quantum algorithm is proposed based on the original work in [4] for treating SVD problems of interest in structural dynamics. The performance of the algorithm, in terms of accuracy and efficiency, is assessed in conjunction with various numerical examples.

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UNCERTAINTY QUANTIFICATION AND RELIABILITY ASSESSMENT OF BUCKLING RESTRAINED BRACES USING MACHINE LEARNING-ASSISTED SIMULATIONS

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ABSTRACT

Buckling Restrained Braces (BRBs) have a significant role in seismic protection, offering lateral support to structures like buildings and bridges in earthquake-prone regions. They are used both for reinforcing aging structures and in new constructions, due to their remarkable energy dissipation capacity, ductility, and stiffness. This study conducts an in-depth probabilistic analysis of BRBs, assessing their sensitivity and reliability under various conditions such as different gap sizes, friction coefficients between the encasing and steel core, and other geometrical and mechanical properties of the connecting materials. This problem has been analyzed by integrating numerical analysis, machine learning, and Monte Carlo simulation (MCS) to evaluate the reliability level of these braces. This analysis is conducted to quantify the reliability level of the investigated BRBs and establish the resistance factors necessary to maintain the reliability level above prescribed thresholds.

Additionally, this study quantifies the reliability of BRBs, focusing on the impact of filler materials on both the local and overall performance of these braces. Filler materials can vary, ranging from concrete, grout, mortar, to granular substances like compacted aggregate. Additionally, options like lightweight or lean concrete are explored for their potential in reducing the total weight of the structure. These considerations are crucial for optimizing BRB design and ensuring their effectiveness in seismic protection.

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FEATURE ENCODED AND MULTI-RESOLUTION PHYSICS-INFORMED MACHINE LEARNING APPROACHES FOR MUSCULOSKELETAL DIGITAL TWIN APPLICATIONS.

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ABSTRACT

Machine Learning (ML) offers efficient approaches to identify biological system properties from physiological measurements, e.g., motion data and raw surface electromyography (sEMG), providing opportunities to construct a subject-specific musculoskeletal (MSK) digital twin system for health condition assessment and motion prediction. While physics-informed ML tools for dynamic systems offer learning capabilities that satisfy the conservation laws, physics-informed time-domain mapping of high-frequency muscle excitation signals to low-frequency joint motion remains challenging due to dissimilarities in the frequency contents between the muscle excitation signals (input) and motion data (output). In this work, we first developed a Feature-Encoded Physics-Informed Parameter Identification Neural Network (FEPI-PINN) for the simultaneous prediction of motion and parameter identification of human MSK systems. Here, the features of high-dimensional sEMG signals were projected onto a low-dimensional noise-filtered embedding space for effective forward dynamics training. This FEPI-PINN model can be trained to relate sEMG signals to joint motion and simultaneously identify the key MSK parameters. To enhance time-domain mapping, a Multi-Resolution Recurrent Neural Network (MR-RNN) learning algorithm is further proposed. In this approach, the fast wavelet transform is applied to mixed frequency sEMG signals, decomposing them into nested multi-scale signals. The prediction model is first trained with lower-resolution input signals using a gated recurrent unit (GRU), and the trained parameters are then transferred to the next higher-scale training. These training processes are repeated recursively until a full-scale training is achieved. Numerical examples demonstrate that the proposed framework can effectively identify subject-specific muscle parameters with noisy sEMG signals, and the trained physics-informed forward-dynamics surrogate yields accurate motion predictions of elbow flexion-extension motion, which are in good agreement with the measured joint motion data.

DEVELOPMENT AND USE OF AXIAL LOADING TEST DATABASE FOR ANALYSIS AND DESIGN OF DRILLED SHAFTS IN SOFT ROCK

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ABSTRACT

More accurate analysis and economical design of drilled shaft in soft rock presents a great challenge to practitioners. There are several reasons: (a) our lower understanding of in-situ soft rock property, behavior and its interaction with shaft (e.g., shaft shearing, tip end bearing or combination of both); (b) our lower confidence in the methods used for analysis and design that are often disconnected with real (in-situ) data and simplistic (e.g., empirical correlations of shaft shearing and tip end bearing resistance with rock compressive strength based on load tests at multiple sites which were not interpreted in a consistent manner); and (c) difficulty to quantify and incorporate the construction effect on shaft behavior into analysis and design (e.g., shaft roughness, base debris and socket smear).

At present, three procedures developed during the 1980s still remain the principal means of analysis and design of rock-socketed pile. The WJD method is empirical and makes use of normalized shaft shearing stress/tip end bearing pressure-settlement curves and design charts that were developed from the results of about 50 field tests and makes (Williams et al. 1980). The RA method used a series of numerical solutions to account for non-slip and slip between the pile shaft and surrounding rock and establish the design curves (Rowe and Armitage 1987). The third is the CK method based on analytical models and empirical data to address elastic and non-elastic behavior (Carter and Kulhawy 1988). In addition to capacity, all of three methods can predict the load-movement response of rock-socketed pile, providing practitioners with more information to support their decision-making. This paper presents a large database of 363 loading tests on drilled shaft in soft rock. Predictions of load-settlement curve, load at a set of specified settlement or pile movement at serviceability loading are compared with load test results. The results are presented in the form of the mean, coefficient of variation and probability distribution of the ratio of measured over predicted load or movement.

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UNCERTAINTY-AWARE AUTONOMOUS ROBOTIC INSPECTION BASED ON ACTIVE VISION

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ABSTRACT

In this study, an artificial intelligence framework based on active vision is developed to facilitate the use of robotics for autonomous visual damage inspection. While considerable progress has been achieved by utilizing state-of-the-art computer vision approaches for damage detection, these approaches are still far from being used for autonomous robotic inspection systems due to the existence of uncertainties in data collection and data interpretation. More specifically, current autonomous inspection systems are predominantly passive and agnostic about the presence of damage during damage collection. Consequently, these systems adhere to predefined inspection paths or require human guidance. Moreover, passive systems struggle to rationalize the presence of damage when inconsistencies arise among the detection outcomes from various observations.

To address these gaps, this study proposes a framework based on computer vision, stochastic control process, and decision and information theories combined with novel computer graphics methods that will enable robots to select the best course of action (e.g., move to the right, left, up, down, etc.) for active perception (i.e., information gathering) while searching for defective regions and accounting for existing uncertainties and constraints (e.g., the robot's battery life). By doing so, the required information is collected efficiently for a better understanding of damage severity and, hence, more reliable decision-making. More specifically, the proposed framework for decision-making under uncertainty is developed by formulating the active perception as a Partially Observable Markov Decision Process (POMDP). To this end, a deep reinforcement learning (DRL) agent is generated to learn the optimal policy for the proposed decision-making framework.

Compared with the previous study, this study incorporates uncertainty estimation in both the perception network and the policy network to identify uncertain detections and actions undertaken by the agent. Additionally, the agent harnesses the power of transformer architectures to process long time horizons of information, enabling improved attention to diverse observations. Furthermore, the selection of the next-best viewpoint is expanded from 2D to 3D space. As a test case, the proposed framework is rigorously evaluated for autonomous assessment of cracks on metallic surfaces to demonstrate its capabilities.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEEP LEARNING FOR MODEL CORRECTION

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ABSTRACT

Despite many recent advances and new deep learning technologies, training of the Deep Neural Networks (DNNs) for modeling of unknown systems generally requires large amounts of high-fidelity training data. Such large quantities of data may not be available in many practical applications, hence it is of importance to develop methodologies that can accurately correct imperfect prior models given scarce amounts of high-fidelity data. Hence, utilizing the Flow-Map DNN methodology and transfer learning, we present a model correcting framework and demonstrate its effectiveness on several numerical examples.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ORIGINS OF THE POROELASTIC NOORDBERGUM EFFECT

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ABSTRACT

Reverse water level effect [1], also known as Noordbergum effect [2], refers to the counterintuitive rise of fluid level in a water well during early times after starting groundwater withdrawal from a nearby well. The effect is known to be a result of the coupling between pore water flow and solid phase deformation in the rocks comprising an aquifer system. Poroelastic models which have captured the Noordbergum effect are predominantly based on numerical simulations. An exception is the solution of Verruijt [2] which includes a number of simplifying assumptions. Further, the existing literature on the subject presents a divided and rather dubious set of explanations for the underlying causes of this effect.

An analytical solution for poroelastic coupling [3] in a multisequence ground water system is herein presented. Pore fluid withdrawal from the groundwater system is modelled through a finite line sink. The solution rigorously captures the Noordbergum effect. Results indicate that the contrast in mechanical properties of the water-producing and adjacent layers determines the occurrence, and if so, the strength of the effect. Conversely, contrasting flow properties of sequences in the absence of any mechanical heterogeneity would not trigger the Noordbergum effect.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Contributions of high-performing lightweight materials to sustainable development and infrastructure resilience of engineering systems

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELECTROCHEMICAL PROPERTIES OF EXPANDED SHALE, CLAY, AND SLATE LIGHTWEIGHT AGGREGATES IN GEOMECHANICALLY REINFORCED STRUCTURES

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ABSTRACT

This paper presents experimental investigations on the corrosion rate of galvanized and carbon steel reinforcements in geo-structural backfills like mechanically stabilized earth (MSE) walls. Investigations include electrochemical properties of expanded shale, clay, and slate (ESCS) lightweight aggregates (LWA). The study highlights electrical resistivity, pH, sulfate, and chloride testing using existing standards and proposes new standards based on advanced electrochemical techniques relying on the electron loss flow, like linear polarization resistance (LPR) or Tafel extrapolation. Rendering correlations between physical, mechanical, and electrochemical properties of ESCS LWA indicate their contribution to reducing corrosion and extending the service life of geo-mechanically reinforced structures. These benefits are vital to reducing environmental footprints and enhancing the resilience of infrastructure development.

AN EXPERIMENTAL INVESTIGATION OF INTERNALLY CURED CONCRETE USING PALLETIZED LIGHTWEIGHT EXPANDED CLAY AGGREGATES

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ABSTRACT

Existing research has shown the effectiveness of internal curing using lightweight aggregates in extension of the service life of concrete materials. The presented project addresses the application of palletized lightweight expanded clay aggregates (LECA) in pumpable concrete mixtures. Specimens included two grades of lightweight aggregates with different density and water absorption rates. Experimental investigations include testing physical and mechanical properties of specimens with wet curing, air curing, and internal curing. Results highlight the influence of curing methods and aggregate grades on tensile, compressive properties of concrete and cementitious mortar.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATIC/DYNAMIC BEHAVIOR OF PARTIALLY SATURATED CONCRETE: FULLY COUPLED DEM/CFD STUDIES

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ABSTRACT

This study investigates the effects of free water on the compressive and tensile properties of concrete under two-dimensional (2D) mesoscale conditions, both static and dynamic. The effect of free pore water content on the static and dynamic mechanical properties of concrete (strength, brittleness, and fracture) was primarily examined. A fully coupled DEM/CFD technique formed the basis of a pore-scale hydro-mechanical model [1], [2], which was used to predict the behavior of both partially and fully fluid-saturated concrete. The method's concept was creating a network of channels between discrete elements in a continuous space to produce a flowing movement. Concrete that was partially wet and had minimal porosity was suggested to have a two-phase laminar fluid flow (air and water). To accurately track the liquid/gas content, the position and volumes of the pores and cracks were taken into account. Bonded granular specimens of a simplified spherical mesostructure that mimicked concrete were subjected to several static and dynamic numerical simulations in both wet and dry conditions. The numerical DEM-CFD investigations into the impact of saturation level on static and dynamic concrete strength and fracture were extensive. It was found that the saturation level significantly affected the mechanical behavior of the concrete. The dynamic compressive and tensile strengths increased and the quasi-static tensile and compressive strengths decreased with the fluid saturation. Because of the slow deformation, the concrete mesostructure allowed for fluid movement in the static range, and there were noticeable variations in the pore fluid pressures and velocities. Reduced strength resulted from the pore fluid pressures promoting the rate of fracture. Because of the high strain rate and fast loading, the concrete mesostructure inhibited fluid migration in the dynamic range, and pore fluid pressures and velocities changed very little. Strength was enhanced as a result of the pore fluid pressures slowing the rate of fracture. The numerical DEM-CFD results matched the corresponding findings of the laboratory tests.

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Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VARIATIONS IN THE DEVELOPMENT LENGTH OF A HIGH-STRENGTH STEEL WIRE IN A BRIDGE CABLE UNDER THE INFLUENCE OF WRAPPING FORCE AND AXIAL LOADING

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[1]Columbia University

ABSTRACT

Bridge cables use thousands of steel wires packed in a hexagonal pattern wrapped by bands around the surface. The stiffness plays a vital role in structural integrity and safety. This paper studies cylindrical wires packed in a hexagonal lattice tightened by wrapping bands at certain stress intervals. The stress transferred through the contacts between the wires can be represented by a center-center force network with the Hertz contact. The singum model simulates the contact forces by the stress between continuum particles and predicts a transversely isotropic effective stiffness of the cable, which changes with the wrapping force. When a wire is broken, the stress transfer among the wires can be estimated by stress analysis of the homogenized cylinder with the finite element method, which illustrates the development length changing with the wrapping force and axial loading. When the wrapping force is small and axial loading is large, a larger development length is predicted due to the slip between the broken wire and its neighbors and the lower stiffness in the cross-section. Given a wrapping force, the critical development length is obtained at the critical axial load.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY QUANTIFICATION AND SENSITIVITY ANALYSIS OF MID-RISE TIMBER BUILDINGS UNDER FIRE HAZARD

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ABSTRACT

The structural damage of timber buildings subjected to fire is dictated by the fire severity and fire resistance of structural members. The fire severity in turn depends on the fire load density and ventilation factors which continuously evolve during a fire scenario thus introducing significant uncertainties. In addition to this, the mechanical and thermal properties of structural members and fire-protection membranes are characterized by a certain degree of variability. As a result of this, the fire performance of a timber building can exhibit significant randomness. For instance, changes in ventilation conditions during fire resulting from a compartment wall failure or breaking of a glass window affect the fire growth and hence the structural damage. In this context, this research addresses the uncertainty quantification in fire performance of an innovative mid-rise timber building through a MATLAB-based uncertainty quantification framework (UQLab). Structural responses that are critical to the collapse probability are identified and the Sobol' sensitivity indices of those responses in relation to the input parameters are estimated. Moreover, the practical application of probabilistic approaches for structural fire engineering is limited due to the lack of efficient techniques. Herein, surrogate models based on the Multiplicative Dimensional Reduction Method (M-DRM) and the Polynomial Chaos Expansion (PCE) are used to get valuable insights into the probability of failure. These results can be effectively used to guide structural fire designers to identify key parameters in the design process and give emphasis to details that can alter the global fire performance of timber buildings.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRADIENT ENHANCED PHYSICS-INFORMED RADIAL BASIS NETWORK BASED PDEM FOR EFFICIENT RELIABILITY ANALYSIS OF STRUCTURE

Sourav Das[1] *and Solomon Tesfamariam**[1]

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ABSTRACT

Reliability analysis is a critical aspect of ensuring the dependability and performance of complex systems in various engineering domains. The Probability Density Evolution Method (PDEM) has emerged as a powerful tool for assessing the reliability of systems by modeling the evolution of probability density functions over time. It integrates probability theory and mathematical modeling to analyze the time-dependent behavior of systems, which is described by partial differential equations. By solving the PDEs, the PDEM facilitates the computation of probability density functions at different time points, enabling a comprehensive understanding of the system's reliability dynamics. In this study, a gradient-enhanced physics-informed radial basis network (g-PIRBN) is proposed to solve the PDEs in an efficient manner. In general, the physics-informed neural network (PINN) is commonly used to solve PDEs. The residuals from the PDE and physics constraints are used as a loss function of the neural network. It is seen that it needs many training samples to achieve accuracy. Here, a gradient-enhanced network is used, which uses the gradient information of the residuals. With this in view, g-PIRBN is proposed, in which the loss function of the network is constructed as a summation of residuals and its gradient and radial basis function is used as an activation function. For numerical demonstration, a SDOF system under free vibration and an 8-storey frame subjected to nonstationary ground motions are used to establish the proposed g-PIRBN with the aim of reducing training points compared to PINN. Also, the influence of random parameters on the evolution of PDF and second-order response statistics is quantified for stochastic structures.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL STUDY OF INJECTION-INDUCED RESERVOIR DAMAGE DURING GEOLOGICAL CARBON STORAGE USING PHASE FIELD MODELLING APPROACH

Jianwei Tian[1] and Adedapo Awolayo[1]*

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ABSTRACT

Geological carbon storage, particularly in saline aquifers and decommissioned oil and gas reservoirs, plays a pivotal role as carbon sinks to achieve global net-zero emissions targets. Natural fractures and heterogeneities are often found in many consolidated geological settings, necessitating the consideration of fracture properties in relation to diverse fluid-rock interactions for accurate predictions of the efficiency and integrity of these CO2 storage sites [1]. In addition, long-term CO2 injection into heterogeneous reservoirs can induce hydrogeological changes, influencing the hydraulic properties of both the aquifer and caprock [2]. Such alterations can result in the propagation of inherent fractures, which can compromise the containment of CO2 storage and generate potential leakage pathways [3]. This study developed a coupled thermal-hydro-mechanical-damage model to simulate the CO2 injection-induced fracture propagation within the reservoir and caprock. We integrated the phase field approach for formation damage modelling with subsurface fluid transport, providing a comprehensive analysis of the fracture propagation patterns under various horizontal stress ratios and injection pressure. The results indicate that variations in stress ratios, reservoir pressure, rock strength properties, and geological discontinuities affect fracture propagation paths of the reservoirs and the integrity of its caprock. The study provides more insights into the evaluations of injection-induced reservoir damage and the potential leakage pathways.

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Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MACHINE LEARNING-BASED TIME SERIES PREDICTION FOR NODAL NETWORKS UNDER UNCERTAINTY

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ABSTRACT

Engineering systems modeled as nodal networks operate as a function of the individual nodes comprising the network as well as the links connecting the nodes. These systems are subject to multiple sources of uncertainty, including uncertainty at the nodal level and uncertainty in the operations of links between nodes. Predicting characteristics at the nodes of a system, including predicting demands at individual nodes in the network, provides critical information on the functioning of the system during both normal operations and under hazard scenarios. Accurate time series predictions to support decision making, however, is challenging, under conditions of uncertainty and complex system behaviors.

In this work, we present a new approach for time series prediction in nodal networks. In addition to consideration of historical information as in traditional time series prediction approaches, we include information from neighboring connected nodes in the network to perform the prediction. We do this by building on a recurrent neural network architecture and, in particular, the architecture of gated recurrent units (GRUs). We create a new structure that we call the Pairwise-GRU that is able to take into account both historical information and neighboring node information to perform time series prediction. The result is the ability to predict nodal characteristics at each node in the network.

We apply the proposed approach to predict demands at nodes in an electrical power network in the southeastern United States. Using data from both normal operating conditions and under hazard scenarios such as flooding, we evaluate the performance of the prediction under both conditions. Results show increased accuracy and decreased uncertainty compared to results from existing approaches in the prediction at nodes across the network under both normal operating and hazard conditions. In addition, the proposed approach is found to perform particularly well for multiple time steps ahead prediction. Finally, the prediction is achieved in comparable computational time compared to existing approaches. The prediction is accomplished on the order of seconds on a standard machine to produce accurate and confident predictions to support decision making under uncertainty for nodal networks.

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATING ACTIONS TO INCREASE INFRASTRUCTURE RESILIENCE THROUGH A BAYESIAN SYSTEM MODELING FRAMEWORK

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ABSTRACT

Critical infrastructure systems are operating under an increasing range of hazard conditions with components that are often aging. With limited resources to repair, retrofit, or perform other actions to increase the performance of these systems, it is critical to be able to accurately evaluate potential infrastructure investments to select and prioritize those actions that will result in the largest improved impacts on predicted performance. The complexity of infrastructure systems and the uncertainties across the hazards and component- and system-level performance outcomes makes such accurate and computationally efficient evaluations challenging on an infrastructure system scale.

In this work, we evaluate a range of potential actions to increase infrastructure resilience to hazards using a proposed Bayesian network-based system modeling framework. The framework enables us to achieve computationally tractable reliability assessment results with exact inference results at each component in the system and across the full extent of an infrastructure network. We present results from evaluating the impacts of three major types of potential infrastructure investments to increase infrastructure performance: retrofitting or replacing components to decrease component-level vulnerabilities, adding service provision redundancies in the system to increase resilience, and adding links in the system to change network configurations.

We apply the proposed framework to a water distribution network with dependencies on the electrical power system. Inferences from the framework provide exact values in quantifying changes in component- and system-level performance based on the varying potential actions. Comparing the outcomes enables us to draw conclusions on the actions most effective in decreasing infrastructure vulnerability and increasing infrastructure resilience. A second water distribution system with dependencies on electrical power is analyzed to assess generalizability of the outcomes. Results show the types of components that are most sensitive to any variations in network parameters; the characteristics of the infrastructure components that are most effectively addressed with retrofits, replacements, or increased redundancies; and the recommended locations of new links in a connected system.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-OBJECTIVE OPTIMIZATION APPROACH FOR PLACING WATER LEVEL SENSORS IN COASTAL COMMUNITIES FOR REAL-TIME REGIONAL RISK ASSESSMENT

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ABSTRACT

Increasing storms and flooding are leading to increasing impacts of these natural hazard events on buildings, lifelines, and populations along the coast. Accurate and comprehensive regional risk assessment requires an understanding of water levels at a hyperlocal level across a coastal community. New technologies, including real-time water level sensors, provide a way to understand these water levels at a high resolution and in real time across a community. However, with limited resources for installation and maintenance of these sensors across a region, strategic decisions and placement of these sensors is needed to provide accurate and comprehensive regional hazard estimation and risk assessment.

In this work, we present a new multi-objective optimization-based approach to locate high-resolution water level sensors in a coastal community. Information from the sensors provide hyperlocal real-time water level information across a community to support regional hazard estimation and risk assessment. In the optimization process, we expand the parameters considered for the network of sensors beyond traditional measures of network coverage and network uncertainty to include new flood-specific parameters including hazard estimations of flood likelihood and critical infrastructure exposure, serviceability including sensor accessibility, and measures of social vulnerability including a socio-economic index and a vulnerable residential communities index. We use this full suite of parameters to find the non-dominated solution set of sensor locations for water level sensor placement.

We apply the proposed approach to the coastal community of Chatham County, GA, building on an ongoing collaboration between the researchers and city and county officials. In addition to the multi-objective optimization approach, we propose an integrated workflow for sensor placement decision-making that combines the quantitative optimization analyses with local expertise and experience to choose the final sensor locations. In the application of the proposed approach, from the full set of 28,890 possible locations, we successfully reduce the size of the set to a much smaller optimal and feasible set of 381 potential new sensor locations. This result represents just 1.3% of the full solution set. Additionally, we find the solutions to be able to be further reduced to dozens of clusters to facilitate community decision-making in placing new sensors across the community for regional risk assessment.

Complex dynamics and vibration control of infrastructure exposed to single/multiple hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECENT DEVELOPMENTS IN SURROGATE AND DIGITAL TWIN MODELING OF TALL BUILDINGS

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ABSTRACT

Simple beam models, such as shear and Timoshenko beams, have been used for many years to model the response of high-rise buildings, in the low frequency range, in which the wave propagation is essentially one dimensional. As they are described by only few parameters and analytical solutions for their responses exist, they are convenient for use as generic structural models in studies of phenomena, regional loss assessment and structural health monitoring (SHM). Recently, two new models were proposed by the authors, cantilever pyramid beam and cantilever beam with exponentially graded rigidity, deforming in shear [1,2]. Exact analytical solutions for their responses were derived in term of Bessel functions and generalized to chains of beam elements. Parametric studies show the effect of tapering/grading on the ratios of modal frequencies and shape of transfer functions and impulse response functions and are useful for interpretation of recorded response of full-scale buildings. The models were applied to system identification, from earthquake records, of two instrumented buildings, the pyramid shaped 48-story Transamerica Tower in San Francisco, California [1] and Tongde Plaza Yue Center (TPYC), a 51-story skyscraper in southwest China [2]. The parameters were identified by a wave method, developed by the authors, involving matching of pulses in impulse response functions.

A detailed 3D finite element model of the TPYC was developed recently in OpenSees, comprising the tower, basement, pile foundation and surrounding soil [3]. The results show that the modal frequency and damping are significantly influenced by the stiffness of the soil, even for such a tall building on piles, while the travel time of pulses in impulse response functions through the tower are not sensitive to the properties of the soil. This is an important advantage of the wave method for SHM over methods based on detecting changes in modal frequencies.

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Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE COMPUTATIONAL MODELING OF THERMO-HYDRO MECHANICAL BEHAVIOR FROZEN SOILS SUBJECTED TO LONG-TERM FREEZING AND THAWING CYCLING

Danyang Tong[1], Giuseppe Buscarnera[1], Alessandro F. Rotta Loria[1], David Grégoire[2], Gilles Pijaudier-Cabot[2] and Gianluca Cusatis[1]*

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ABSTRACT

Permafrost is a class of geomaterials consisting of permanently frozen soils that cover almost a quarter of the Northern Hemisphere onshore land. However, as a result of global warming and recursive temperature fluctuations above and below 0°C, permafrost is experiencing both thawing and heaving, which causes a degradation of its structure, properties, and behavior. The thawing of permafrost not only threatens many ecological processes, including nutrient and carbon cycling but also results in the deepening of the active layer. In conjunction with frost heave, which involves a volumetric swelling of wet soils upon freezing, permafrost thawing can induce damage to critical infrastructure in the Arctic and high-altitude regions, such as roads, airport runways, building foundations, and energy pipelines. Currently, limited tools are available to model the influence of recursive cycles of thawing and freezing on the structure, properties, and behavior of permafrost. As a result, the development of a robust modeling tool to predict the mechanics of permafrost subjected to freezing and thawing cycles represents a significant yet complex opportunity, whose efficacy depends on the ability to adequately capture the interactions between the multiple phases that constitute such material: soil particles, crystal ice, unfrozen water, and water vapor. This study addresses this challenge by proposing a thermo-hydro-mechanical (THM) model to simulate the long-term multi-physical behavior of frozen soils subjected to cyclic temperature variations, considering the phase change between unfrozen water and ice, pore water pressure variations, and their influence on the deformation and strength evolution of such material. The THM model is implemented in Lattice Discrete Particle Modeling (LDPM) to simulate these complex processes at the pore scale.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVAERT NETWORKS: A DATA-DRIVEN FRAMEWORK FOR MODEL SYNTHESIS AND IDENTIFIABILITY ANALYSIS

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ABSTRACT

Current deep learning based data-driven approaches have prioritized the task of emulation for physics-based systems. However, due to their remarkable flexibility, these data-driven architectures can be naturally extended to model synthesis, inversion, and identifiability analysis.
In this work, we present the inVAErt networks, a comprehensive data-driven framework for modeling parametric physical systems. InVAErt includes a deterministic neural emulator and a decoder for approximating the forward and inverse maps, respectively, a flow-based density estimator for sampling representative outputs, plus a variational auto-encoder for latent space constructions. The additional latent space compensates for the loss of input-output bijectivity in ill-posed inverse problems and also helps reveal the non-identifiable manifold (a.k.a pre-image or fiber) in the input space that maps to a common output. After these essential components are trained and tested, we can perform fast and comprehensive model analysis/synthesis. We examine the proposed method via numerous numerical examples, including simple input-output maps, dynamical systems, and spatio-temporal PDEs.

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Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STUDY OF THE EFFECT OF WINDSHIELD ON AERODYNAMIC PERFORMANCE OF CABLE STAYED BRIDGES USING CFD

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ABSTRACT

The geometric appendages such as hand railings, crash barriers, windshields, maintenance railings, fairings etc., affect the aerodynamic performance of cable-supported bridges. In many cases, modifications to these appendages are made post installation because of certain unforeseen situations during operation. Therefore, it is important to quantify their effect on the aerodynamic performance of a deck section. In the present study, we examine the effect of the windshields on the static and dynamic response and stability coefficients of cable-supported bridges using computational fluid dynamics (CFD). Note that there is limited information on the impact of appendages, such as wind shields, on flutter derivatives (FD).

Two bridge deck section configurations are considered. A 2-dimensional section model of Great Belt East bridge without any geometric appendages and other with attached windshields. Static non dimensional force coefficients are obtained by performing transient simulations for a static deck and obtaining average forces. To obtain the flutter derivatives, a method to determine the rational function approximation (RFA) from forced vibration data is used. FDs are then extracted by using obtained RFA coefficients. CFD simulations are performed using opensource code OpenFOAM 5.0, wherein deck section is modelled as a rigid body. Unsteady Reynold- averaged Navier–Stokes model with K-Omega SST turbulence model is used. Results indicate significant impact of considering windshields in CFD model on static as well as dynamic performance of cable supported bridges.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RISK-BASED DESIGN OF INERTER VIBRATION ABSORBERS UTILIZING EMBODIED ENERGY SUSTAINABILITY CRITERIA

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ABSTRACT

Inerter-based vibration absorbers (IVAs) have emerged as a popular strategy for the protection of buildings against earthquakes. Recent efforts have developed a bi-objective optimization framework to examine the trade-off between building performance and IVA size/forces for nonlinear structures. Those studies showcased the importance of explicitly considering nonlinear structural behavior in the design phase and revealed the complex relationship of that importance to the details of the performance quantification and the excitation intensity (the latter impacting the degree of nonlinear behavior). This work extends these earlier efforts, establishing an efficient multi-objective design using a risk-based performance quantification that comprehensively accounts for variabilities in the seismic hazard intensity. Furthermore, emphasis is placed on the ability of IVAs to promote sustainability stakeholder priorities. This is accomplished by quantifying seismic losses through the embodied energy associated with repairs. The proposed framework is applicable to any seismic protective device, though the emphasis here is on IVA variants: the tuned-mass-damper-inerter (TMDI) and tuned-inerter-damper (TID), with the tuned-mass-damper (TMD) also covered as special case. The performance quantification is established based on a performance-based earthquake engineering (PBEE) formulation that relies on nonlinear response history analysis (NLRHA) to define structural response and on an assembly-based vulnerability estimation to quantify seismic consequences. To promote computational efficiency a reduced order model (ROM) formulation is adopted. The ROM is first calibrated to match the nonlinear finite Element Model (FEM) response without any seismic devices and is subsequently used to replace the FEM in all NLRHAs needed in the design optimization, dramatically reducing computational burden. The PBEE implementation supports the estimation of the mean annual frequency of exceedance curves for the (i) embodied energy associated with seismic losses and (ii) peak IVA forces (representing IVA size/cost). This information is subsequently used to define appropriate risk-metrics (annual expected values or thresholds for different return periods), and a multi-objective problem is formulated considering the aforementioned competing responses (i-ii). A stochastic search approach is developed to efficiently identify the Pareto front for different variants of this design problem. The case study reveals the utility of the overall framework in analyzing trends across the design variants and guiding risk-informed decisions for the level of protection offered by different IVA devices.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A GRAPH-BASED ADJOINT DESIGN SENSITIVITY ANALYSIS APPROACH FOR TRANSIENT SYSTEMS WITH HISTORY DEPENDENT MATERIAL RESPONSE

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ABSTRACT

We present a graph-based adjoint sensitivity analysis method for transient systems with history dependent material response. It is straightforward to implement, benefits from automatic differentiation and accommodates various adaptive time-stepping schemes and constitutive models. The computed sensitivities pass the Taylor verification test and are thus consistent with the discretize and differentiate approach. We demonstrate the method by computing shape sensitivities for dynamically loaded linear elastic structures and quasi-statically loaded elastoplastic structures.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

POLY-MATERIAL LATTICE DISCRETE PARTICLE MODEL (P-LDPM) FOR THE NUMERICAL SIMULATION OF SCRATCH TESTING

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ABSTRACT

Fracture mechanics of quasi-brittle materials, such as concrete, wood, and ceramics, have significantly evolved in recent years. Understanding fracture properties of quasi-brittle materials is of extreme importance in analysis and prediction of their mechanical behavior. Among many methods used to investigate fracture properties of quasi-brittle materials, scratch testing has arisen recently as a promising method for determining such properties. Although numerous analytical and experimental studies on scratch testing of concrete, mortars, rocks, etc., exist in the current literature, nevertheless, no in-depth work on the numerical simulation of scratch testing involving a complete understanding of complex phenomena, such as the transition depth of cutting between ductile and brittle regimes, has been carried out so far. In this work, the Poly-Material Lattice Discrete Particle Model (P-LDPM), an extension to the single-material LDPM, which has shown its capability to successfully simulate cement-based structures by considering the spatial distribution of their constituents, is used to analyze and predict thoroughly numerical scratch testing. The spatial structures of cement-based materials are built using NIST’s Virtual Cement and Concrete Testing Laboratory (VCCTL). The scratch testing predictive ability of P-LDPM is then validated using experimental data found in the literature.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AUTOMATIC DETECTION AND QUANTIFICATION OF SPALLING DAMAGE LEVEL IN REINFORCED CONCRETE ELEMENTS USING FOUNDATIONAL MODELS

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ABSTRACT

Bridge inspection is critical for ensuring the safety and long-term functionality of road systems; however, out of the 3,717 bridges in Peru, fewer than 26% have undergone any inspection throughout their operational lifespan. Despite having guides and procedures, the current traditional inspection of bridges is prone to errors, and subjectivity, and is time-consuming. Moreover, a select team of qualified engineers is required to periodically inspect a growing number of reinforced concrete (RC) bridges. Acknowledging these challenges, there is a need for efficient solutions to accelerate and automate on-site inspection of bridges. This paper proposes and discusses a fully automated, vision-based system for detecting and quantifying spalling in RC elements using deep learning and foundational models. The proposed approach involves the data collection of concrete spalling in real structures, incorporating physical measurements of diameters, segmentation models, retrieval of spalling diameter, and damage quantification. Leveraging recent advancements in AI-based computer vision, we conducted a comparative analysis between convolutional neural networks (CNNs) and foundational models for spalling segmentation. For CNNs, we used the U-Net architecture, and for foundational models, we utilized the Segment Anything Model (SAM) in combination with Grounding DINO. Based on the results, the proposed system (based on foundational models) demonstrates the capability to accurately segment and retrieve physical properties of spalling, allowing to quantify the damage level according to established guidelines for bridge inspection. The proposed system serves as a promising guide for applying foundational and prompt-based models to civil engineering datasets.

CONNECTOR AND BEAM LATTICE (CBL) MODEL FOR THE SIMULATION OF WOOD UNDER HIGH STRAIN RATES

Matthew Troemner[1], Susan Alexis Brown[1], Hao Yin[2] and Gianluca Cusatis[2]*

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ABSTRACT

In the quest to mitigate climate change impacts within the architectural and structural engineering domains, the shift towards sustainable construction materials, particularly Engineered Wood Products (EWP), has become increasingly pivotal. This study introduces the innovative Connector and Beam Lattice (CBL) model, as a novel computational tool for simulating the mechanical behavior of wood under high strain rates. This model is especially relevant in the context of extreme loading scenarios like blasts and impacts, which are essential considerations for the application of EWPs in critical infrastructure.

The CBL model's development is informed by the urgency to enhance structural resilience against catastrophic events, as exemplified by incidents such as the Oklahoma City Bombing and the Beirut warehouse explosion. These events underscore the vulnerability of conventional structures, traditionally reliant on materials like reinforced concrete, to high-energy impacts. EWPs emerge as a sustainable alternative, offering not just lower CO2 emissions and carbon sequestration during growth, but also a potential for reduced environmental impact in the construction sector.

At the heart of the CBL model is a mesoscale 3D lattice framework, designed to replicate the intricate cellular mesostructure of wood. Utilizing a Voronoi-based domain discretization, the model features thin-walled, curved 3D Timoshenko beams aligned in the parallel-to-grain direction, mimicking the natural straw-like cell structure of wood. The beams' axes, representing the joints of cell ridges with cruciform cross-sections, are derived from adjoining cell walls. The incorporation of the Isogeometric Analysis (IGA) technique allows for an accurate representation of these curved geometries, essential in capturing the true mechanical behavior of wood.

A novel aspect of the CBL model is the integration of 1D zero-length cohesive elements, or connectors, placed transversely. These connectors, essential in representing the in-plane deformability of cell walls, link adjacent beams and account for the material properties' differentiation between the longitudinal connectors and the beam lattices. This differentiation is crucial, as it symbolizes the weak-joints between wood fibrils, a fundamental factor in realistically simulating wood's fracturing behavior.
The CBL model represents a significant advancement in material science and engineering, offering a comprehensive and precise tool for predicting the behavior of EWPs under challenging conditions. This research supports the sustainable use of wood in crucial infrastructures and empowers the design of more resilient, environmentally friendly structures, aiding in the global efforts to adapt to and mitigate the impacts of climate change in the built environment.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MULTI-FACTOR DECISION FRAMEWORK TO INTEGRATE SAFETY AND POLICY IN OPERATIONAL AND MAINTENANCE PLANNING FOR OFFSHORE WIND FARMS

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[1]Northeastern University
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ABSTRACT

Offshore wind energy is expected to become an increasingly important and dependable energy source in the future, owing to its numerous advantages. However, maintaining offshore wind turbine (OWT) structures is a challenging and costly task, receiving more attention from researchers and industry experts. To enhance the durability, safety, reliability, and resilience of these structures beyond existing standards, several obstacles must be addressed. These issues do not conform to a single modeling paradigm and necessitate a multi-domain approach.

A condition-based maintenance strategy, which combines relevant information about the current condition of OWTs with statistical models of failure risk, cost, and worker safety, is proposed in this work. The decision-making framework proposed here follows cumulative prospect theory's general framing and valuation conventions. It consists of three phases: in Phase I, the technical state of the OWT is assessed; in Phase II, a set of contingencies and outcomes are constructed, expressed in terms of economic and safety impact; finally, in Phase III, a decision model is formulated that assesses the value of all possible interventions and chooses an appropriate action.

The proposed framework consists of a simulation-optimization approach for planning and scheduling maintenance operations for offshore wind farms and finding the optimal intervention solution for minimizing costs while keeping a high availability of wind turbines and guaranteeing safety standards for workers. Several parameters and constraints are addressed to account for the realistic complexity of the problem, such as weather conditions, resource cost, and maintenance duration. Several scenarios are experimented with to demonstrate the approach efficiency during the farm's life cycle.

Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARATIVE ANALYSIS OF FORMULATIONS FOR PERIODIC BOUNDARY CONDITIONS IN SOLID MECHANICS

Timothy Truster[1] and Amirfarzad Behnam[1]*

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ABSTRACT

The presentation provides an in-depth comparative analysis aimed at evaluating the effectiveness and computational efficiency of various periodic boundary conditions and homogenization methods in the context of nonlinear multiscale analysis. Two types of field variables, namely fluctuation fields and total displacement fields, are employed for this analysis. The fluctuation field utilizes volumetric integrals, while the total displacement field employs interface integrals to compute homogenized macro stress and strains, yielding different accuracies and high-performance efficiencies. Additionally, four distinct methods, including multipoint constraint (MPC), Lagrange multipliers (LM), penalty method, and discontinuous Galerkin (DG) method, are used to investigate the varying levels of accuracy and high-performance efficiency offered by each method. Various measurements are employed to evaluate the accuracy of results for each method and their high-performance capabilities concerning both direct and iterative solvers. Results indicate that the discontinuous Galerkin method exhibits the highest accuracy for macrostrain values. The weak enforcement of boundary conditions by the discontinuous Galerkin method leads to a balancing of error between surface and volume contributions, enhancing overall accuracy. Furthermore, the multipoint constraint method, with its strong enforcement of boundary conditions, demonstrates the lowest runtime due to a condensed number of degrees of freedom. Another significant comparison involves iterative and direct solvers, revealing that while iterative solvers are considerably faster when they converge, they encounter convergence issues in methods involving Lagrange multipliers. In contrast, direct solvers take more time but exhibit robust convergence across different methods.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE ANALYSIS OF FLUID-STRUCTURE INTERACTION INVOLVES COMPLEX GEOMETRY UNDER WAVE AND CURRENT EFFECTS

Wen-Huai Tsao[1] and Christopher Kees[1]*

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ABSTRACT

The multiscale analysis of fluid-structure interaction focuses on the application of the Cut Finite Element Method (CutFEM) to analyze the wave dynamics and current effect on structures with complex geometry based on the multi-phase Navier-Stokes model [1]. Instead of employing adaptive quadrature or local refinement for the cell meshes near the fluid-solid interface, CutFEM CutFEM utilizes Nitsche's method to directly enforce the no-slip condition on the cut cell while maintaining optimal accuracy in boundary-conforming meshes. This approach facilitates the use of 3D structure models obtained from pre-existing STL files or LiDAR scanners. Numerical validation is conducted through wave-flume experiments in both small and prototype scales. In small-scale experiments, the analysis focuses on the dynamics of a ship in a steady current, with numerical reconstruction of the wakes in front of and behind the ship. The advantages of reducing meshing work for the wake are highlighted. In prototype-scale experiments [2], the study simulates wave propagation over mangrove forests, assessing hydrodynamic drag induced by prop root structures without the need for parameterization in physical experiments. The wave attenuation and force reduction are evaluated. Numerical results and experimental measurements are compared in both examples. This research highlights the potential of CutFEM and multiscale modeling techniques to enhance the design of coastal ecosystems and marine structures. By accurately simulating structural responses to waves and current effects, the approach provides valuable insights for the development of resilient and sustainable coastal infrastructure.

Keywords: CutFEM, Multi-phase Navier-Stokes flow, Fluid-structure interaction, Natural-based shoreline, Ship wake.

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Uncertainty characterization and propagation in complex nonlinear structures

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PARAMETRIC STUDY AND UNCERTAINTY QUANTIFICATION ON WAVE ATTENUATION AND HYDRODYNAMIC IMPACT MITIGATION INDUCED BY MANGROVE FORESTS

Wen-Huai Tsao[1], Ying-Chuan Chen[2], Lance Manuel[3] and Christopher Kees[1]*

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ABSTRACT

Natural and nature-based features play a vital role in coastal engineering, particularly for storm defense, ecosystem rejuvenation, and stabilizing shorelines. Our prior research [1] utilized the Cut Finite Element Method (CutFEM) to replicate complex wave motions through mangrove forests. The reduced-order model, which represents actual mangrove forests, was validated for its damping characteristics and induced wave attenuation. The present study offers a parametric analysis that seeks to explore how random (or uncertain) wave and current intensities might impact the hydrodynamic drag induced by mangrove trees. The volume-averaging method is employed to separately analyze the drag induced by different parts of the mangrove's prop root system. This approach doesn't need additional tuning parameters or experimental measurements and also avoids the excessive computational costs associated with refining the mesh around the roots. The frequency-domain approach employed is integrated to quantify the dynamic response in representing two key outputs: the wave elevation behind the mangrove forests and the hydrodynamic forces acting on a downstream protective wall. Results will be compared with experimental measurements provided by OSU [2] to validate the proposed surrogate model, which will seek to account for uncertainties in performance in terms of drag and wave attenuation. The approach outlined allows for a comprehensive assessment of the effectiveness of natural-based facilities in reducing wave impact and mitigating structural damage. The helps to enhance our understanding of wave-structure interactions and offers a robust framework for advanced coastal and marine design.

Keywords: Natural shoreline, CutFEM, Parametric study, Uncertainty quantification, Fluid-structure interaction.

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Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AI BASED REGISTRATION OF BIM AND AS-BUILT POINT CLOUD FOR SMART CONSTRUCTION PROGRESS MONITORING

Girma Zewdie Tsige[1], B.S.A Alsadik[1] and S.J. Oude Elberink[1]*

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ABSTRACT

In construction automation applications, registration between 3D Building Information Modelling (BIM) and the point cloud obtained by remote sensing technology is critical for smart monitoring of construction progress. The existing AEC/FM software packages for 3D data registration implement coarse registration manually, which is less accurate and more time-consuming. This work presents a novel column-based coarse registration method. The method is based on the extraction of columns from the as-built point cloud, then followed by aligning with the corresponding columns from the BIM model to get the the best transformation parameters. For the point cloud data, fully automated column extraction techniques are used by applying deep learning. We selected the point-based KPConv deep learning model and applied a transfer learning technique to extract columns from the as-built point cloud which is acquired by UAVs and terrestrial laser scanners. The model is trained and tested with the published publicly available indoor point clouds and the point clouds from the real construction site. The trained model was evaluated on the test dataset and achieved a column detection accuracy of 69%.

Then, we propose an automatic coarse registration method that is motivated by the Random Sample Consensus (RANSAC) algorithm. This approach is presented to estimate the transformation parameters that best align the point cloud in the coordinate frame of the BIM model by matching the corresponding columns. Experiments were carried out on as-built point clouds acquired from the real building construction site using both terrestrial laser scan (TLS) and unmanned aerial vehicles (UAV) to validate the proposed method. The results show that our proposed column-based registration method achieved a rotation error of 0.02 degrees and RMSE of 0.12 meters for the TLS dataset and 0.03 degrees and 0.17 meters for the UAV dataset. We conclude that our proposed approach contributes to automating the registration between the as-built point cloud and the as-planned BIM model to monitor the construction progress.

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Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ORIGAMI OF MULTI-LAYERED SPACED SHEETS

G. Wayne Tu[1] and Evgueni Filipov[1]*

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ABSTRACT

Two-dimensional (2D) origami tessellations such as the Miura-ori are often generalized to build three-dimensional (3D) architected materials with sandwich or cellular structures. However, such 3D blocks are densely packed with continuity of the internal material, while for many engineering structures with multi-physical functionality, it is necessary to have thin sheets that are separately spaced and sparsely connected. This work presents a framework for the design and analysis of multi-layered spaced origami, which provides an origami solution for 3D structures where multiple flat sheets are intentionally spaced apart. We connect Miura-ori sheets with sparsely installed thin-sheet parallelogram-like linkages. To explore how this connectivity approach affects the behavior of the origami system, we model the rigid-folding kinematics using analytic trigonometry and rigid-body transformations, and we characterize the elastic-folding mechanics by generalizing a reduced order bar and hinge model for these 3D assemblies. The orientation of the linkages in the multi-layered spaced origami determines which of three folding paths the system will follow including a flat foldable type, a self-locking type, and a double-branch type. When the origami is flat foldable, a maximized packing ratio and a uniform anti-shear capacity can be achieved by strategically choosing the link orientation. We show possible applications by demonstrating how the multi-layered spaced origami can be used to build deployable acoustic cloaks and heat shields.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISCOELASTIC SOLUTION FOR MODE I ENERGY RELEASE RATE IN AVIATION PAVEMENT REFLECTION CRACKING MODEL

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ABSTRACT

In 2020, the Federal Aviation Administration (FAA) developed a two-dimensional model of its full-scale, indoor reflection cracking test equipment at the National Airport Pavement Test Facility (NAPTF), William J. Hughes Technical Center, Atlantic City International Airport, NJ. The analytical model represents two jointed concrete slabs with a continuous hot mix asphalt overlay, and with a single, preexisting vertical crack in the overlay centered on the joint. Previous effort in modelling treated the asphalt overlay as an elastic material and allowed to determine stress intensity factor for Mode I of crack opening.

A further viscoelastic generalization of the model, which is presented here, became possible due to the viscoelastic-elastic correspondence principle. Appropriate fictitious elastic problem is formulated in integral transform domain. The general solution of that fictitious elastic problem of two governing equations was sought in the form of potentials.

Mode I energy release rates (ERR) were derived from superposition of the linear elastic solutions of two separate problems having different domains. The first problem considers the uncracked domain with the same prescribed horizontal displacements at the bottom as the original problem. The second problem considers the cracked domain, where horizontal displacements at the bottom boundary are prescribed to be zero. The sum of the solutions of these two problems in the transform domain gives the desired Mode I solution at the vicinity of the crack tip. By applying Schapery's theory of crack propagation in viscoelastic materials, this model was used to determine the ERR in asphalt overlay subject to Mode I cracking caused by repeated temperature-induced loads. Computed ERR values showed good agreement with ERR values computed by a finite element model (ABAQUS).

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MICROMECHANICAL MODEL OF CONCRETE CREEP

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[2]Applied Research Associates

ABSTRACT

Our study presents a three-dimensional micromechanical model for concrete creep at early age. In this model concrete is treated as a two-phase composite material with an aging matrix (cement paste) and inclusions (aggregates). The uniaxial creep behavior of the aging matrix is described by Bazant's solidification theory, which models aging by volume growth of nonaging viscoelastic products of cement hydration. However, the bulk modulus of the matrix is assumed to be time-independent and the inclusion behavior is assumed to be elastic. The Mori-Tanaka scheme is adapted for determining the effective shear and bulk creep operators of the composite material. To enable numerical determination of concrete creep compliance and relaxation functions, continuous integral operators are approximated by matrix operators acting in finite-dimensional spaces. Effective creep operators (which represent overall properties of the composite) are evaluated as rational functions with matrix arguments.

Multiscale organization, mechanics and physics of layer-like, fibrous materials and related structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TAILORING MECHANICAL PROPERTIES OF SELF-HEALING FIBER-REINFORCED POLYMER COMPOSITES

Jack Turicek[1], Vikita Kamala[1], Ghadir Haikal[1] and Jason Patrick[1]*

[1]North Carolina State University

ABSTRACT

Fiber-reinforced composites (FRC) exhibit superior mechanical properties arising from a hierarchical material makeup. The informed selection of reinforcement/matrix, and incorporation of functional components (i.e., interlayers, sensors, vasculature) can engender dynamic and tunable properties, thereby producing high-performance FRC for a wide range of applications from aerospace to civil infrastructure. However, the layered architecture in commonly laminated FRC renders these materials susceptible to interfacial damage (i.e., delamination), characterized by debonding of reinforcing fibers from the matrix. One promising delamination mitigation strategy relies on the inclusion of poly(ethylene-co-methacrylic acid) (EMAA) thermoplastic interlayers that toughen the composite against mode-I fracture while also enabling in situ self-healing to repair cracks via thermal remending [1, 2, 3]. However, the effects of softer thermoplastic inclusions beyond mode-I fracture behavior (e.g., shear), have not been fully explored.

In this talk, we detail an experimental study (supported by numerical modeling) to better understand the effect of thermoplastic interlayer inclusions on the mechanical properties of FRC via a 3-point flexure (i.e., short beam shear) geometry. Through an in-depth investigation, we reveal the ability to tailor both the interlaminar shear strength (ILSS) and mode-I fracture resistance (GIC) by varying the 3D printed EMAA density and interlayer placement. Moreover, we demonstrate nearly full restoration of ILSS over ten consecutive heal cycles while repeatedly achieving over 100% fracture resistance. These latest findings provide a sound pathway for the multifunctional design of composite materials that inherit self-healing abilities without detriment to structural integrity.

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Leveraging structural sensing and monitoring for informed decision-making, mitigation, and post-event management
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING FUNCTIONAL RECOVERY OF INSTRUMENTED BUILDINGS THROUGH INTEGRATED NONSTRUCTURAL AND STRUCTURAL DAMAGE AND LOSS ASSESSMENT

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ABSTRACT

The integrity and functionality of buildings during and after seismic events rely on the performance of both nonstructural and structural components. While substantial progress has been made in assessing the seismic performance of instrumented buildings, there is limited understanding of assessing nonstructural components (NSCs), despite their significant contribution to the overall economic loss. According to FEMA E-74, NSCs account for a significant portion of building replacement costs across different building types, which can result in long-term disruptions, expensive repairs, and potential hazards. This paper aims to develop a nonlinear model-data fusion (NM-DF) approach for post-earthquake functional recovery assessment of instrumented buildings by performing high-resolution seismic response and damage assessment for both nonstructural and structural components. The NM-DF is implemented using a recently developed nonlinear model-based state observer, which improves the prediction accuracy of a structural model of a building by combining the model with a limited number of response measurements to reconstruct the full dynamic response. The proposed method of approach consists of four steps: 1) seismic response measurements, 2) model-data fusion and dynamic response reconstruction, 3) structural and NSCs damage assessment, and 4) seismic loss and functional recovery modeling. The results are employed to quantify the functional recovery of instrumented buildings. The quantified loss metrics, such as repair costs and functional recovery, provide stakeholders with clear insights into the post-event condition of the building. They support informed decision-making for post-event occupancy planning, as well as for repair and rehabilitation if necessary.

The effectiveness of this approach is demonstrated using data from buildings instrumented by the California Strong Motion Instrumentation Program (CSMIP), specifically those subjected to the 1994 Northridge Earthquake. By utilizing sensor measurement data, a nonlinear model-based observer of the building is implemented using OpenSeespy to reconstruct the complete seismic response by effectively capturing the nonlinearities in the system. The estimates obtained from the observer are used for seismic damage, loss, and functional recovery assessment and compared with the available post-earthquake assessment reports.

Keywords:
Functional Recovery, Nonlinear Model-Data Fusion, Nonstructural Components, Damage Assessment, Loss Assessment, Instrumented Buildings

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ELECTRONIC, ELASTIC AND PHONON PROPERTIES OF WN2 (194 & 187) BY DFT APPROACH

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[2]King Fahd University of Petroleum and Minerals

ABSTRACT

Abstract

Here, the structural, electronic, elastic, and phonon properties of WN2 compounds having hexagonal phases but different space groups (194 and 187) and concertation's are investigated by first-principles calculations. The results of the electronics properties show that the band gaps decrease with an increase in the same ratio of the concertation's of tungsten (W) and nitrogen (N) content for the WN2 (187) tungsten dinitrides. The concertation differences have no significant impact on the elastic properties of these two compounds. The lower enthalpy of formation of these compounds indicates their stability in thermodynamics. Furthermore, no negative frequency bands were observed in the phonon dispersion bands, which confirmed the dynamical stability of these compounds.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TRANSIENT MODELING AND DESIGN OPTIMIZATION OF BIODEGRADABLE MAGNESIUM ALLOY FIXATION DEVICES

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[1]Johns Hopkins University

ABSTRACT

Biodegradable magnesium (Mg)-based alloys have shown promising applications as medical implant materials for treatment of musculoskeletal injuries with proposed uses as fixation devices and scaffolds within the orthopedic and oral/maxillofacial fields, respectively [1]. Challenges remain in taking full advantage of the beneficial mechanical properties and osteopromotive phenomena of these novel materials. Focusing on the current standard of care for nonunion long bone fracture fixation which utilize stiff, inert metallic intramedullary nails (IMNs), improvements to conventional design methods are needed which will properly account for material moduli discrepancy between native cortical bone under fixation and stiffer IMN materials in order to reduce “stress-shielding” effects of fracture zone volumetric bone loss [2]. Simulating Mg alloy biodegradation and the concurrent bone remodeling processes of this biomechanical environment necessitates development of time-step analysis techniques to capture physics-based properties of the bone-IMN complex at its various remodeled-degraded states, respectively. Thus, a design optimization scheme is proposed which incorporates transient IMN material loss surface-to-volume relations using experimentally observed Mg alloy in vivo corrosion rates along with bone remodeling behavior using strain-based bone-density evolution algorithms from literature [3] into a transport process PDE-based topology optimization framework to control local fracture region stress states under simulated biomechanical loading by optimizing for desirable transient stiffness and target bone stress profiles. Transient stability, strength, and robustness (“safety-factor”) constraints are formulated into the optimization algorithm along with volume constraints and manufacturability limits such as minimum feature size. This optimization scheme is demonstrated on 3D bone-IMN design problems optimized for controlled IMN biodegradation to gradually increase fracture zone loading over time. The potential value of this methodology to produce novel IMN designs which stimulate bone remodeling and reduce current risks of post-operative fractures in relation to existing IMN designs is illustrated through performance comparisons of stress and stiffness metrics at multiple states throughout a recovery period.

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Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NONLINEAR DYNAMIC ANALYSIS OF STRUCTURES EQUIPPED WITH ECO-FRIENDLY HYSTERETIC DEVICES BY USING NEXTFEM DESIGNER

Nicolo' Vaiana[1] and Giovanni Rinaldin[2]*

[1]University of Naples Federico II
[2]NextFEM

ABSTRACT

Nowadays a continuously growing attention is paid to the development of vibration control strategies that employ devices manufactured by means of production processes and/or mate-rials in line with the respect of the environmental sustainability principles and sustainable development. These devices typically exhibit a nonlinear behavior characterized by complex force-displacement hysteresis loops [1].

Vaiana and Rosati [1-3] have recently proposed a unified approach to simulate such complex responses. The novel model, denominated Vaiana Rosati Model (VRM), offers a series of advantages with respect to other models available in the literature. Indeed, it: (i) adopts closed form expressions, or equivalent rate equations, for the evaluation of the generalized force, tangent stiffness, and work, (ii) allows for the description of the vast majority of complex hysteresis loops, (iii) permits the independent simulation of the loading and un-loading phases by means of two different sets of eight parameters, (iv) requires a straight-forward calibration of the parameters thanks to their clear theoretical and/or experimental significance, (v) can be easily implemented in a computer program.

To encourage researchers and designers to adopt the VRM for research and practical purpos-es, we demonstrate its accuracy by performing some numerical tests in NextFEM Designer. In particular, we first employ the recently implemented model to compute the nonlinear dy-namic response of a structure equipped with eco-friendly hysteretic devices and, subsequent-ly, we compare the results with those obtained by modeling the devices with other models available in the computer program.

[1] Vaiana N, Rosati L (2023) Classification and unified phenomenological modeling of complex uniaxial rate-independent hysteretic responses. Mechanical Systems and Signal Processing 182: 109539.

[2] Vaiana N, Capuano R, Rosati L (2023) Evaluation of path-dependent work and internal energy change for hysteretic mechanical systems. Mechanical Systems and Signal Processing 186: 109862.

[3] Vaiana N, Rosati L (2023) Analytical and differential reformulations of the Vaiana-Rosati model for complex rate-independent mechanical hysteresis phenomena. Mechanical Systems and Signal Processing 199: 110448.

Eco-friendly systems, devices, and metamaterials for structural vibration control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL MODELING OF UNBOUNDED FIBER-REINFORCED ELASTOMERIC ISOLATORS WITH RECYCLED RUBBER

Shiv Prakash[1], Nicolò Vaiana[1] and Daniele Losanno[1]*

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ABSTRACT

Seismic hazard has been a big woe to humankind since the beginning of time. Several passive control strategies have been deployed during the last decades to minimize the losses due to recurring destructive seismic events. Elastomeric bearings are one such class of devices that uses alternate layers of rubber and reinforcements to mitigate the seismic hazards oncoming various built structures. Even if steel plates were conventionally adopted in the past, fiber reinforcement has been recently introduced due to various benefits like cost-effectiveness and efficiency. Unbonded fiber-reinforced elastomeric isolator (UFREI) is one such fiber-reinforced elastomeric bearing device, which is connected to neither the superstructure nor the substructure. The low cost of these devices can be attributed to lower manufacturing and installation costs, while the better seismic efficiency can be mainly attributed to a unique rollover phenomenon with higher isolation effectiveness.

Recently, a greener approach of using scrap tires and rubber leftovers as elastomeric layers in UFREI has been proposed to replace the earlier use of natural or synthetic rubber. Waste rubber poses a severe environmental threat, hence promoting recycling process with novel base isolation systems will also have a great impact on the environment and general well-being. Such eco-friendly bearings are generally termed Recycled-rubber unbounded fiber-reinforced elastomeric isolators (RU-FREI). The properties of the elastomer compound made of reclaimed rubber can be significantly different from common natural or synthetic rubbers due to expected lower mechanical performance. In the present study a numerical finite element modeling of RU-FREI is investigated starting from preliminary characterization of the compound. Based on experimetnal results on small-size specimens, a properly calibrated model is developed to reproduce the hysteretic beahavior of the device. Promoting the use of RU-FREIs can significantly reduce seismic risk in non-engineered buildings of developing regions of the World.

New trends in vibration control and energy harvesting: Modeling and analysis of innovative materials and structures at micro- and macro-scale

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RECENT ADVANCES ON THE EVALUATION OF PATH-DEPENDENT WORK AND INTERNAL ENERGY CHANGE FOR MECHANICAL SYSTEMS WITH COMPLEX HYSTERETIC BEHAVIOR

Nicolò Vaiana[1] and Luciano Rosati[1]*

[1]University of Naples Federico II

ABSTRACT

Nowadays, accurate modeling and design processes, adopted in aerospace, civil, mechanical, and naval engineering, require a profound understanding of the actual behavior exhibited by mechanical systems. When material nonlinearities are considered, the actual responses of mechanical systems become notably complicated due to their typical hysteretic nature.

In hysteretic mechanical systems it is possible to identify two types of generalized forces, denominated, respectively, generalized conservative and non-conservative forces. The former (latter) perform generalized path-independent (path-dependent) work. Among generalized non-conservative forces, it is possible to distinguish between generalized rate-dependent and rate-independent hysteretic forces that are, respectively, function of generalized velocities and displacements.

In the current engineering literature, some fundamental definitions, representing the basis of the classical mechanics, are not always properly adopted in the study of hysteretic mechanical systems; in addition, phenomenological models, typically employed for the simulation of the behavior exhibited by such systems, do not allow for a straightforward and, at the same time, accurate calculation of generalized work and energy components associated with generalized forces having a non-conservative nature.

With the aim of shedding light on the definition and evaluation of work and energy components, the nonlinear equilibrium equations of a conventional family of MDOF hysteretic mechanical systems are first derived and, subsequently, the modified work-energy theorem is introduced. In addition, to allow for a forthright evaluation of path-dependent work and internal energy change associated with generalized rate-dependent (rate-independent) hysteretic forces, the related (closed form) expressions are derived by adopting the Seleemah and Constantinou (Vaiana and Rosati) model. The former is capable of simulating both linear and nonlinear rate-dependent hysteretic responses; the latter can simulate a great variety of complex rate-independent hysteretic behavior, characterized by symmetric, asymmetric, pinched, S-shaped, flag-shaped hysteresis loops or by an arbitrary combination of them [1-3]. Finally, several nonlinear dynamic analyses are performed on a MDOF hysteretic mechanical system to clearly describe its free vibration and forced harmonic vibration responses in terms of work and energy quantities.

[1] Vaiana N, Rosati L (2023) Classification and unified phenomenological modeling of complex uniaxial rate-independent hysteretic responses. Mechanical Systems and Signal Processing 182: 109539.

[2] Vaiana N, Capuano R, Rosati L (2023) Evaluation of path-dependent work and internal energy change for hysteretic mechanical systems. Mechanical Systems and Signal Processing 186: 109862.

[3] Vaiana N, Rosati L (2023) Analytical and differential reformulations of the Vaiana-Rosati model for complex rate-independent mechanical hysteresis phenomena. Mechanical Systems and Signal Processing 199: 110448.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

METEOROID IMPACT-INDUCED PEAK SHOCK PRESSURE AND ATTENUATION THROUGH THE THICKNESS OF A REGOLITH PROTECTIVE LAYER ON A LUNAR STRUCTURE

Sushrut Vaidya[1] and Ramesh Malla[1]*

[1]University of Connecticut

ABSTRACT

Lunar base structures must withstand multiple extreme conditions associated with the Moon's environment, including low gravity, hard vacuum, ionizing radiation, large temperature variations, moonquakes, and meteoroid impacts. A regolith cover of adequate thickness may serve as a protective shield for lunar facilities, safeguarding structures against several of these major environmental hazards, including radiation, temperature fluctuations, and meteoroid impacts. This paper presents a novel methodology, based on analytical and computational modeling, for predicting peak shock pressure and its attenuation in hypervelocity meteoroid impacts on regolith shielding. Such hypervelocity impacts (HVI) are characterized by extremely high impact velocities and pressures, as well as impact-induced shock waves and likely phase changes in the impactor (meteoroid) and target (regolith layer). The proposed approach is based on the physics of HVI-induced shock waves and utilizes an analytical model known as the planar impact approximation. The impact is modeled as a one-dimensional hydrodynamic phenomenon involving semi-infinite bodies. Impedance matching conditions are used to calculate the initial shock pressure and energy partition between the impactor and target. The model also yields an estimate of the timescale for the initial compression stage of the impact, which is used as an approximation of the duration over which the peak impact pressure acts on the target. Linear shock velocity-particle velocity equations of state are used to model material behavior under shock loading. The propagation of the impact-induced shock wave within the regolith layer, accompanied by attenuation of shock pressure, is analytically modeled by assuming a hemispherical shock front geometry and neglecting the irreversible energy loss associated with the heating of the regolith as the shock wave expands into the target. The analytical model is verified by comparing its predictions with computational results reported in the literature, for an impact scenario involving a dunite impactor and dunite target. A preliminary finite element (FE) model is also developed to simulate hydrodynamic behavior in HVI events. Considering a thick target (regolith layer) and various spherical impactors (meteoroids), parametric analyses are carried out using the analytical and FE models to study the attenuation of shock pressure through the regolith thickness. The predictions of the analytical and computational models are compared and used to determine the regolith thickness required for decay of shock pressure to the yield strength of the underlying structural layer. The methodology presented in this paper could provide practical tools for engineering design of meteoroid impact-resistant regolith shielding for lunar structures.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXISTENCE, UNIQUENESS AND MULTIPLICITY OF RANS SOLUTIONS IN TERMS OF THE INITIAL VORTICITY

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ABSTRACT

Similar to the Navier-Stokes problem, there are proofs of local existence in time for Euler's Equations. However, it remains unknown if there are weak global solutions in the Euclidean space of dimension 3. It is also not known if given a regular initial condition there is a solution that does not develop singularities in finite time. A significant breakthrough in this aspect is the Beale-Kato-Majda Theorem, which guarantees that if a solution becomes irregular within a finite period, its vorticity will escalate infinitely as the time limit approaches. Our objective is to demonstrate that the initial vorticity plays a crucial role in determining the existence and uniqueness of local solutions over time for the Reynolds-Averaged Navier-Stokes Equations and its limit as the kinetic viscosity approaches zero. Furthermore, we demonstrate how the estimation for the duration of existence is influenced by the parameters.

LEARNING MODELING ERRORS VIA A MACHINE-INFUSED BAYESIAN MODEL UPDATING APPROACH

Mohammad Valikhani[1], Kasra Shamsaei[1] and Hamed Ebrahimian[1]*

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ABSTRACT

Physics- and mechanics-based models are commonly used for response prediction of complex systems. Accuracy of model predictions depends on the level of modeling errors. Mathematical simplifications and assumptions, and lack of understanding about the underlying physics can introduce modeling error or model form uncertainties in model predictions. Modeling error is a critical bottleneck in traditional Kalman filtering and Bayesian model updating approaches as it results in biased estimation of unknown parameters and disparages the uncertainty quantification capabilities. To solve this problem, here we propose a novel machine-infused Bayesian model updating framework to account for modeling error in nonlinear material models in structural dynamics problems. To this end, a recurrent neural network (RNN) representing the material model error is augmented within the material-level of the physics-based model. Parameters of the infused RNN model are estimated using a sequential Bayesian data assimilation method from the measured system-level inputs and outputs of the structure, i.e., the infused RNN is trained using indirect data. Within this presentation, the theoretical and computational aspects of this new machine-infused physics-based model updating framework will be presented, and its performance will be validated using numerically simulated data.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIRTUAL SENSING OF WIND TURBINE DRIVETRAIN USING MULTIBODY DYNAMICS MODEL INVERSION

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ABSTRACT

Wind turbine drivetrains are prone to fatigue and failure. Studies have shown that drivetrains are among the main contributors to the operation and maintenance costs of wind turbines. Common modes of damage in drivetrain system include bearing failure, fatigue crack, and material defects. There is general agreement that operational conditions such as transient loadings are the primary driver of damage. Direct measurement of the loading applied to the drivetrain system and the resulting force demands in components such bearings and gears are not practically feasible. In this study, virtual sensing via multibody dynamics model (MDM) inversion is proposed to estimate unknown loads applied to the drivetrain and predict stress at the inaccessible locations. To this end, stochastic MDM is built assuming that unknown loads are random variables, and then a sequential Bayesian inference method is employed to estimate unknown loads using measurement data. Case studies have been conducted to validate the methodology and predict responses in the key components to estimate remaining fatigue life.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS INFORMED NEURAL NETWORKS FOR HETEROGENEOUS POROELASTIC MEDIA

Sumanta Roy[1], Chandrasekhar Annavarapu[1], Pratanu Roy[2], Brice Lecampion[3] and Dakshina Murthy Valiveti[4]*

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ABSTRACT

Subsurface systems are inherently complex, with intricate coupling among various physical processes, often necessitating computational modeling due to the impracticality or expense of direct measurements. Prevailing computational modeling frameworks are classified into two broad categories – physics-based models, and data-driven models. Physics-based models represent the physical processes mathematically through partial differential equations, solved using numerical techniques like the finite element method. However, generating meshes, especially conforming to subsurface features, is computationally intensive, acting as a significant pre-processing bottleneck. In contrast, data-driven models use machine learning for predictions. Model accuracy depends on the volume and caliber of available training data, and often sparse subsurface data constrains the effectiveness of purely data-driven models.

Physics-informed neural networks (PINNs), a hybrid approach, integrate physics-based and data-driven modeling [1]. These methods minimize a loss-functional based on governing physical principles using deep neural networks, eliminating the need for conforming meshes and extensive training datasets. Our study focuses on developing a PINNs framework for poroelasticity in heterogeneous materials. Although PINNs have been applied to model poroelasticity before [2], these studies are limited to homogeneous materials where the governing equations describing solid deformation and fluid flow are only loosely coupled. We propose a modified PINNs framework addressing these limitations. Firstly, a composite neural network is introduced, using distinct networks for each output field variable (displacement and pressure), sharing activation functions but trained independently for other parameters. Secondly, to address heterogeneity, we seamlessly integrate it into the Interface-PINNs (I-PINNs) framework, employing different activation functions across material interfaces to capture solution field and gradient discontinuities accurately [3]. Furthermore, we assess a single neural network architecture and compare it against our proposed framework. The performance of our modified PINNs architecture is also compared with conventional PINNs through benchmark examples. The results show that the proposed method is better suited for heterogeneous poroelasticity problems in terms of both accuracy and cost.

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Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISLOCATION DISTRIBUTION IN MEDIUM ENTROPY ALLOY CRCONI USING MICROPILLAR COMPRESSION TESTS AND MOLECULAR DYNAMICS SIMULATIONS

Mobin Vandadi[1] and Nima Rahbar[1]*

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ABSTRACT

This study analyzes the deformation mechanisms in single-crystal medium entropy alloys (MEAs) shaped into micropillars. Employing an experimental and simulation approach, we compressed these micropillars to a strain of 10%. We utilized dark-field transmission electron microscopy (TEM) to observe the resultant dislocation distribution within the post-deformed structure. This method allowed for precisely visualizing the internal dislocation networks following deformation.

Simultaneously, molecular dynamics simulations were conducted to provide a theoretical perspective on the dislocation behaviors observed. These simulations elucidated the underlying mechanisms that govern dislocation formation and movement within the micropillars. A significant focus of our study was to determine the impact of the short-range order of elements on the dislocation distribution within these alloys.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ION DIFFUSION RATE IN SOFT WOOD STRUCTURES: A MOLECULAR DYNAMICS STUDY

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ABSTRACT

The study of ion and chemical diffusion within secondary plant cell walls is crucial for optimizing the application of biomasses. This research focuses on understanding how moisture-induced glass transition in amorphous polysaccharides, such as amorphous cellulose and hemicelluloses, influences inorganic ion diffusion through these cell walls. Despite extensive experimentation, the detailed mechanisms of ion interactions with water and hemicellulose molecules still need to be more adequately understood.

Our study employs molecular dynamics simulations to explore the diffusion mechanisms of potassium and chloride ions in secondary plant cell walls under varying moisture levels. We discovered that increased moisture facilitates the formation of solvent layers around ions, diminishing the charge interaction with wood polymers' functional groups and enhancing ion diffusion. Interestingly, the simulation results also indicate that higher moisture lowers the glass transition temperature, which aids ion diffusion. In contrast, increased ion concentration has the opposite effect, raising the glass transition temperature and hindering diffusion.

BUCKLING AND LIFT-OFF OF A HEAVY ROD COMPRESSED INTO A CYLINDER

Gert van der Heijden[1] and Rehan Shah[1]*

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ABSTRACT

We develop a comprehensive, geometrically-exact theory for an end-loaded heavy rod constrained to deform on a cylindrical surface. The cylinder can have arbitrary orientation relative to the direction of gravity. By viewing the rod-cylinder system as a special case of an elastic braid, we are able to obtain all forces and moments imparted by the deforming rod to the cylinder as well as all contact reactions. This framework allows for the monitoring of stresses to ascertain whether the cylinder, along with its end supports, is able to sustain the rod deformations. As an application of the theory we study buckling of the constrained rod under compressive and torsional loads, as well as the tendency of the rod to lift off the cylinder under further loading. The cases of a horizontal and vertical cylinder, with gravity having only a lateral or axial component, are amenable to exact analysis, while numerical results map out the transition in buckling mechanism between the two extremes. Weight has a stabilising effect for near-horizontal cylinders, while for near-vertical cylinders it introduces the possibility of buckling purely due to self-weight. Our results are relevant for many engineering and medical applications in which a slender structure is inserted into a cylindrical cavity.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIBRATION-BASED STRUCTURAL HEALTH MONITORING OF AN AGING POST-TENSIONED CONCRETE GIRDER BRIDGE

Menno van de Velde[1], Dimitrios Anastasopoulos[1], Hans De Backer[2], Edwin Reynders[1] and Geert Lombaert[1]*

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[2]UGent

ABSTRACT

In Belgium, as well as in several other countries in the world, a large part of the bridge infrastructure is approaching the end of their design service life. Due to the economic infeasibility of simultaneous large-scale bridge replacements, extending their service life becomes crucial. This has led to a growing interest in different Structural Health Monitoring (SHM) methods, such as vibration-based monitoring (VBM). VBM utilizes changes in modal characteristics (like natural frequencies, displacement mode shapes, strain mode shapes) for detecting, localizing and quantifying structural damage. While natural frequencies are sensitive to the global stiffness of the structure, they are found to be relatively insensitive to local damage and often influenced by environmental factors such as temperature. Strain mode shapes, on the other hand, are more sensitive to local changes in structural stiffness and less sensitive to temperature. These advantages have already been demonstrated through the long-term monitoring of various steel bridges [1]. Additionally, strain mode shapes have been successfully employed for the detection and localization of reinforcement corrosion in concrete beams in controlled lab environment [2], but validation for real-life structures with varying environmental conditions is still needed.

This study focusses on a post-tensioned concrete girder bridge constructed in 1957. The bridge consists of two reinforced outer spans and a post-tensioned midspan of 23m. Severe visual signs of corrosion-induced damage are observed for several of the post-tensioned longitudinal girders, while others appear to be intact. A permanent monitoring set-up that consists of 4 chains of 22 fiber-Bragg gratings (FBG's) each was installed in 2022. The FBG's are measuring longitudinal dynamic and static macrostrains along four of the longitudinal girders. Temperature and operational dynamic strains have been collected for a period of 4 months, and automated modal analyses have been performed to obtain natural frequencies and strain mode shapes at different temperatures. The identified strain mode shapes of the different longitudinal girders, showing different degradation levels, are compared. In addition, the effect of temperature on the natural frequencies and strain mode shapes is investigated.

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Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

METHODOLOGY TO ASSESS AND MITIGATE RISK FROM SEA LEVEL RISE TO WATER DISTRIBUTION INFRASTRUCTURE IN COASTAL COMMUNITIES

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ABSTRACT

As climate change leads to increasing sea levels, coastal communities are experiencing increased flooding. In the coming years, these effects are expected to lead to movements in coastal populations, including displacing building occupants in both commercial and residential buildings. These population shifts mean that utility providers will face shifting demands on their networks over time. This study presents a methodology to characterize the implications of sea level rise-induced flooding for drinking water utility managers at both a component (e.g., pipe) level and county-wide level. This work also makes mitigation recommendations to prepare these systems for continued operations under these changing conditions. Compared to prior studies, this paper considers the implications of sea level rise-induced population displacement along the coast in its risk assessment for lifeline infrastructure. This study incorporates aspects from works in sea level rise modeling, climate change-induced population shifts, and water infrastructure risk assessment to create a projected risk assessment for a water distribution network for the coming decades. Additionally, an emphasis is placed on including mitigation recommendations at various points throughout the study such that systems are able to continuously meet desired performance levels over the coming years. The methodology combines quantitative and qualitative analysis to provide detailed component-specific risk assessment and mitigation measures. High-resolution building datasets are used in combination with sea level rise projections to estimate the magnitude and timeline of the change in demand to the drinking water supply. The methodology is applied to two study areas in Chatham County, GA, on the eastern coast of the U.S. Assessment over a range of study area conditions leads to findings of varying patterns in types of flooding situations on a neighborhood scale, which are presented with corresponding mitigation recommendations to increase community resilience to forthcoming coastal hazards. Finally, a pipe prioritization score combines several factors of interest to systematically highlight pipes that are particularly likely to require intervention to prepare for the changes that sea level rise brings in coastal communities.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

3D RADIANCE FIELD-BASED NOVEL VIEW ANOMALY DETECTION IN INFRASTRUCTURE

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[1]University of Houston

ABSTRACT

We define the problem of bridge scene anomaly detection (scene AD), as the pixel wise identification of anomalies in images compared to misaligned baseline images of 3D bridge structures. Scene AD is crucial in bridge inspection and monitoring for pinpointing pixel-level discrepancies. To address this, we introduce OmniAD, a novel method tailored for pixel-wise AD in 3D scenes, especially for bridges. OmniAD enhances anomaly detection by incorporating student self-attention modules into its reverse distillation architecture, grounded in Knowledge Distillation. We also present two innovative data augmentation techniques based on novel view synthesis to improve scene AD in bridge contexts. The effectiveness of OmniAD and these augmentation methods is validated using the ToyCity dataset, which consists of a miniature replica city in four configurations and images captured of a Viaduct in downtown Houston, a historic bridge measuring 388.62 meters in total length with a main span of 51.82 meters. Our results show that OmniAD outperforms existing AD methods by up to 40%, setting a new standard in scene AD and marking a significant advancement in bridge inspections.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMPACT OF GEOMETRICAL UNCERTAINTIES IN THE PREDICTION OF PRESSURE LOADS ON A LOW-RISE BUILDING USING LES

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ABSTRACT

Accurately assessing wind loads on low-rise buildings is crucial for mitigating potential losses during extreme wind events. Computational fluid dynamics (CFD) has emerged as a valuable tool for studying these loads, with high-fidelity Large-eddy Simulations (LES) offering a detailed analysis of instantaneous fields for direct estimation of turbulent statistics. However, the reliability of LES requires thorough validation to ensure its accuracy in simulating real-world conditions. Our previous research emphasized the importance of establishing similarity in the atmospheric boundary layer (ABL) between wind tunnel (WT) tests and LES simulations to obtain good agreement between experimental and simulated results for the pressure coefficient. However, the validation process revealed that geometrical uncertainties pose another potentially important factor in the assessment of wind loads, especially when considering buildings with a higher level of detail.

This presentation will highlight an example of how a small geometrical uncertainty in a low-rise building geometry affected the validation of CFD simulations with wind tunnel experiments. In initial validation efforts, excellent agreement between simulations and experiments was obtained along most of the building surface, but locally on the building roof, significant deviations in the pressure coefficients were observed. After determining that these discrepancies could not be attributed to insufficient grid resolution, the wind tunnel model was inspected and a slight discrepancy in the location of building equipment on the roof was found. When running updated CFD simulations to match the wind tunnel model geometry, the discrepancies were resolved, and flow visualizations were used to reveal the cause of the high sensitivity to this small geometrical uncertainty.

To conclude the talk we will highlight ongoing investigations that extend beyond isolated buildings to encompass the complex geometrical uncertainties associated with the surrounding urban environment. With these studies, we aim to enhance our understanding of how geometric variations, both on and around low-rise structures, contribute to wind pressure distribution patterns, and explore potential approaches for estimating the effect of geometrical uncertainty in wind loading predictions.

Seismic isolation: Theoretical advancements, experimental insights, and innovative applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL AND NUMERICAL STUDIES ON A LOW COST ISOLATOR BASED ON ROLLING OF A RUBBER SPHERE ON CONCRETE SURFACES.

Sergio Reyes[1], Antonios Katsamakas[1] and Michalis Vassiliou[1]*

[1]ETH Zurich

ABSTRACT

This paper discusses the Rolling Pendulum System [1,2], a low-cost alternative to spherical sliding systems. Instead of sliding, the system relies on rolling of a rubber sphere between two concrete surfaces, one of which is spherical. The rubber decreases the stress concentrations compared to steel rollers and also dissipates energy via increased rolling friction. However, it creeps and takes an oval shape leading to non-bilinear loops. To reduce creep, we place a steel core within the sphere. We experimentally show that the coefficient of rolling friction increases with the compressive load, but does not depend on the sliding friction between the rubber and concrete. The loops are shown to be close to bilinear, when the size of the steel core increases, yet the coefficient of rolling friction remains within the range that is useful for seismic isolation. Finally, we present, calibrate and validate a finite element model [3] that is able to capture the rolling behavior of the rolling sphere, with or without a steel core.

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Computational geomechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PHYSICS INFORMED CONSTRAINED OPTIMIZATION APPROACH TO MODELING GEOMATERIAL VISCO-ELASTOPLASTICTY

Bozo Vazic[1], Eric Cushman Bryant[1] and Kane Bennett[1]*

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ABSTRACT

Geological materials are heterogeneous and contain flaws across scales. Despite many experimental and numerical investigations of their mechanical properties, a lack of understanding persists about the sub-scale physical processes driving their observed thermo-mechanical and fracture behaviors. Combining experimental, numerical, and machine learning (ML) approaches holds great promise for advancing our fundamental understanding of the multiscale nature of geomechanics and our capability for modeling it. In this talk, we discuss recent work of our research group on developing machine learned models leveraging experimental and numerical data. Modeling of pressure-sensitive visco-elastoplastic damage is obtained via extension of classical box-constrained optimization methods. The utility of the model is demonstrated in the solution of dynamic boundary value problems via the finite-discrete element method (FDEM). Numerical examples exhibit widely distributed fracture-coupled damage-ductility in geomaterials.

Advanced analysis for earthquake engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SEMI-ANALYTICAL AND NUMERICAL ANALYSES OF TUNNELS SUBJECTED TO ARBITRARILY INCLINED SEISMIC WAVES

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ABSTRACT

Tunnels are unavoidable in earthquake-prone zones, and thus it is important to analyse the 3D response of tunnels under near-fault ground motion. Most of the past research on the seismic response of tunnels assume vertical propagation of seismic waves, and focus on 2D plane strain analyses of the tunnel cross-section to study the ovaling/racking behaviour of the tunnel. However, the 2D plane strain approximation breaks down in the near-fault zone where the wavefield is quite complex. In this study, we present a modified domain reduction method to numerically analyse the response of infinitely long tunnels under seismic waves. The method modifications are verified by comparing the results against newly developed semi-analytical results for a lined tunnel embedded in a homogeneous linear elastic halfspace subjected to P, SV and SH waves that are incident at an arbitrary angle to the tunnel. Rapid assessment of the tunnel response can be conducted using the semi-analytical tool, which could serve as a design tool. After obtaining the crude design of the tunnel, the modified domain reduction can then be used to conduct detailed analyses on the seismic response of the tunnel including complexities such as soil nonlinearity and inhomogeneity.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRADIENT-BASED SENSOR PLACEMENT OPTIMIZATION FOR STRUCTURAL HEALTH MONITORING SYSTEMS DESIGN BASED ON HYPERCOMPLEX AUTOMATIC DIFFERENTIATION (HYPAD)

Juan C. Velasquez-Gonzalez[1], Juan David Navarro[1], Arturo Montoya[1], Harry Millwater[1] and David Restrepo[1]*

[1]The University of Texas at San Antonio

ABSTRACT

Structural health monitoring (SHM) techniques rely heavily on the quality of data collected by sensors. Thus, sensor placement optimization (SPO) has become an important tool to enhance the collected data quality while keeping costs under control. However, the probabilistic nature of performance metrics such as probability of detection (POD) has limited the use of SPO to expensive meta-heuristic optimization methods that are often problem-specific and inefficient. In contrast, deterministic approaches, such as gradient-based optimization algorithms, remain unexplored. These algorithms are more efficient than traditional meta-heuristics because the sensitivities provide more information about the cost function near each evaluation point, leading to faster convergence rates. However, their rare use is primarily due to the complexities involved in computing sensitivities of the POD curves of SHM systems with respect to input design parameters, especially the sensor location. This work addresses these shortcomings by introducing a novel gradient-based SPO framework. Leveraging accurate arbitrary-order sensitivities of the dynamical response of structural systems computed with hypercomplex automatic differentiation (HYPAD), the framework optimizes sensor layout in SHM systems. Within our approach, sensitivities of the dynamical response with respect to sensor location are used to estimate the parameters describing a POD curve and their dependence on the model input design parameters. These sensitivities are then integrated into an existing state-of-the-art gradient-based optimization algorithm, facilitating efficient and robust design of sensor layouts in SHM systems. This work aims to directly impact the overall performance of SHM systems and contribute to reducing deployment costs, thereby promoting the proliferation of SHM systems.

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN AEROELASTIC EMULATOR COMPRISING SHAPE, FREQUENCY, AND MEAN ANGLE OF ATTACK FOR THE AERO-STRUCTURAL DESIGN OF BRIDGES UNDER NON-SYNOPTIC WINDS.

Sumit Verma[1], Miguel Cid Montoya[1] and Ashutosh Mishra[1]*

[1]Texas A&M University-Corpus Christi

ABSTRACT

Current aero-structural optimization frameworks for wind-sensitive bridges (Cid Montoya, 2023) are driven by the assessment of several key aeroelastic responses, such as buffeting and flutter, under the action of synoptic winds, in which the impact of the time-variant angle of attack on the fluid-structure interaction parameters is negligible. However, bridges can be located in complex terrains (mountainous regions and fjords), which might strongly deflect the incident wind, resulting in different angles of attack. In addition, non-synoptic wind events, such as hurricanes or downbursts, typically involve drastic variations in the time-variant angle of attack. Consequently, it is pivotal to analyze the impact of angle-of-attack-dependent flutter derivatives in bridge responses under non-stationary winds. Several studies have also pointed out that the angle of attack can have dramatic consequences in the magnitude of some flutter derivatives (Diana and Omarini, 2020; Barni et al., 2022) and even instigate flutter instability at lower wind speeds. Thus, it is necessary to incorporate the effect of the angle of attack in the wind-resistant design, leading to a more general and versatile methodology capable of handling both synoptic and non-synoptic wind design scenarios. However, no research has yet investigated the impact of deck shape modifications on the flutter derivatives at different angles of attack and its consequence in the optimal deck shape design. Hence, this study proposes a Kriging-based aeroelastic emulator that considers the deck shape, the frequency of oscillation of the deck, and different mean incident angles of wind on the deck cross-section to obtain the flutter derivatives for the aero-structural design of bridge decks under non-stationary winds. Verified and validated forced vibration simulations using 2D URANS k-ω SST turbulence model and a single degree of freedom deck system are adopted to extract Scanlan´s flutter derivatives. The aeroelastic surrogate model will be later integrated into aero-structural design frameworks for the shape optimization of bridge decks.

Keywords: angle of attack, flutter derivatives, bridge aeroelasticity

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Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIZE EFFECT OF GLUED LAMINATED TIMBER BEAMS BASED ON THE FINITE WEAKEST-LINK THEORY

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[1]TU Wien

ABSTRACT

Wood, a valuable resource that locks carbon dioxide, serves as an effective building material. Designing for economical utilization with an extremely low failure probability, like 10^{-6}, demands a profound understanding of material properties through the accurate definition of their probability distribution functions (PDFs). However, direct identification through experiments or simulations for such low probabilities appears unfeasible, complicated by the dependence of PDFs on geometric size and loading conditions.

The finite weakest-link theory [1] provides a practical solution for quasi-brittle materials, like wood, by employing a scalable probability distribution function (PDF) that combines Weibull and Gaussian distributions. For structures of sufficiently small size, the Gaussian distribution predominates, and the Weibull distribution describes only the far-left tail. As the structure's size increases, the grafted distribution transitions to be dominated by the Weibull distribution. The distribution is scaled based on the size of a representative volume element (RVE) in addition to the structure's size and elastic stresses. For one RVE under tensile stresses, the grafted distribution is defined by four parameters: the Weibull modulus, scale parameter, failure probability of the grafting point, and coefficient of variation. The challenge lies in identifying the parameters, which requires a substantial sample size for sets with diverse geometric sizes or loading conditions.

We identified all the necessary parameters to scale the PDF of the bending strength of glued laminated timber beams. This was achieved by employing simulations of beam sections under a constant bending moment from a comprehensive simulation campaign [2]. These simulations considered discrete cracking and, in some instances, plastic deformations. Material properties of the timber boards were determined deterministically from real timber boards. Furthermore, we enhanced the precision of the parameters by incorporating experimental test results and adhering to established standards. Consequently, this framework provides the PDF of bending strength specific to the beam size, facilitating the quantification of the size effect at both mean and characteristic (5% quantile) levels.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Complex dynamics and vibration control of infrastructure exposed to single/multiple hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMICS OF A PRESTRESSED CONCRETE BRIDGE WITH AN ACCELERATED BRIDGE CONSTRUCTION END-DIAPHRAGM SYSTEM FOR SEISMIC REGIONS

Esteban Villalobos Vega[1], P. Scott Harvey[2], Royce W. Floyd[1] and Omar M. Yadak[1]*

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ABSTRACT

Diaphragms connect parallel girders and assist with the lateral distribution of load in bridge superstructures. Cast-in-place diaphragms are typically used with precast prestressed concrete beams, but the time for forming and curing can be significant. To reduce the impacts on the driving public and the environment, accelerated bridge construction (ABC) techniques have been gaining popularity, but imposing at the same time an additional challenge to projects located in earthquake-prone areas because care must be taken in the way the connections between precast elements are made. This study explores the use of prefabricated diaphragms for ease and rapidity of construction, incorporating at the same time connection detailing for use in medium to high seismic regions to achieve safe behavior and assist the structure in improving its performance under dynamic action. The proposed precast concrete end-diaphragm system—part of a fully precast prototype bridge superstructure including the girders and the deck—is connected by using reinforcing steel bars and ultra-high-performance concrete (UHPC). High-fidelity finite element modeling of the prototype bridge equipped with the proposed diaphragm system is carried out to better understand the load path, and its dynamic behavior under seismic loading, as well as to inform on the viability of the connection detailing. The numerical results are used to guide an experimental campaign to determine the performance of the solution under laboratory conditions. The tests consist of a lateral force applied at the deck level up to failure, to one of the end sections of the prototype bridge at half scale. Details on the experimental results will be presented.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Reliability analysis and rare event probability estimation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NOISE-AWARE STOPPING CRITERIA FOR ACTIVE LEARNING RELIABILITY WITH NOISY LIMIT-STATES

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ABSTRACT

Reliability analysis is a field of uncertainty quantification that is concerned with computing the probability that a particular system fails. At the core of reliability analysis lies the limit-state function, a possibly expensive-to-evaluate computational model that predicts whether the system fails or not for a given set of input parameters. The main challenge in reliability analysis is that an accurate estimation of the failure probability typically requires numerous limit-state evaluations, leading to unfeasible computational costs. To address this challenge, surrogate models such as Gaussian processes may be employed. These are inexpensive models that approximate the limit-state function using training data obtained through few evaluations of the latter. Active learning methods enhance this approach by iteratively selecting the most informative data points, thereby efficiently refining the model accuracy with minimal computational expense.

In parallel, there has been lately an increasing focus on "noisy" models in the uncertainty quantification field, adding significant complexity to reliability analysis. Contrary to traditional deterministic models, which consistently produce the same results for a given set of inputs, noisy models yield different outputs for identical input parameters. The noise component in these models leads traditional active learning methods to overestimate failure probabilities. This issue may be addressed by using active learning approaches tailored to denoising the problem. However, suitable stopping criteria are still lacking. Stopping criteria are crucial for the accuracy and efficiency of active learning approaches. An overly early stop can lead to inaccurate estimates, while a delayed one may result in unnecessary runs of the limit-state function. Although many stopping criteria exist for deterministic models, typically relying on the stability of the estimated probability of failure or the estimated accuracy of the surrogate, these criteria are not suitable when applied to noisy models.

In our contribution, we address two primary challenges related to this problem: (i) the lack of stability in the estimated probability of failure during the denoising process, and (ii) the accuracy limitations of the surrogate model due to the irreducible noise component. To address the stability issue, we propose smoothing the reliability estimation along the iterations. Regarding accuracy, we introduce a noise-aware accuracy measure and assess its convergence using the smoothed estimates. We validate our method using standard benchmark functions and a realistic structural frame model. The results demonstrate that our approach allows the algorithm to effectively converge to the true probability of failure while significantly enhancing the efficiency of the analysis.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ON THE BUCKLING MECHANICS OF MONOFILAMENTS USED IN TOUCH SENSORY PERCEPTION

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ABSTRACT

Despite the fact that fine monofilaments have been used for many years to assess the sensation of touch, going back to the pioneering work of von Frey using horse-hair, and continuing with the widespread use of Semmes-Feinstein probes, it is somewhat surprising that little published work has appeared that directly addresses the mechanics of such systems, and their utility in sensory perception devices. This presentation considers the mechanics of monofilament buckling, its dependence on key geometric and material parameters, and their sensitivities. Although the physiological sensation of touch is subject to a number of uncertainties, the mechanical behavior of a monofilament, as it is compressed, can be accurately modeled with a relatively straightforward analysis.

Assessing the sense of touch is often achieved using the buckling of a monofilament. The Semmes-Weinstein monofilament is a popular set of calibrated probes in which the ability to detect the lightest of touches can be related to physiological scales in order to assess the loss or recovery of feeling in hands, feet, etc. Detecting the sensation of a monofilament that is slowly pushed onto the surface of the skin is calibrated relative to the amount of force required to buckle the monofilament. The key phenomenon here is that when subject to (axial) compression, the monofilament reaches a specific critical value at which buckling occurs, and, on further compression the applied load remains approximately constant as the buckled shape grows. In terms of energy, the element finds it much easier to deform laterally, despite the axial nature of the applied force. The buckling force depends directly on the characteristics of the probe (material, geometry, etc.), and in turn, this can be related back to the perceived sense of touch by using different probes. The presentation includes some larger-scale experiments to complement data taken from commercially available monofilaments used in clinical studies.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING THE CONFINEMENT OF STRUCTURAL MEMBERS WITH AUXETIC ARCHITECTED TRUSS LATTICE MATERIALS FOR CIVIL INFRASTRUCTURE

Thomas Vitalis[1], Andrew Gross[2], Georgios Tzortzinis[3], Brian Schagen[1] and Simos Gerasimidis[4]*

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ABSTRACT

Negative Poisson’s ratio materials are renowned for their high tunability, high energy absorption characteristics, ductility, and high stiffness-to-weight ratios, owing to their unique architectural characteristics. Variations of their geometrical features and unit cell aspect ratios can lead to changes in their post-peak compressive properties and deformation modes. By exploiting the same mechanism that provides a negative Poisson’s ratio inside an interpenetrating phase composite matrix and under the presence of sufficient elastic contrast between the two constituent phases, substantial increases in the confining pressure can occur even with a small volumetric fraction of auxetic reinforcement. In the case of interpenetrating phase composites, the auxetic phase increases the hydrostatic compression of the matrix and bridges crack propagation. Furthermore, a transition from bending-dominated to stretching-dominated struts is observed inside the composites, contributing to favorably enhancing the stress distribution within the truss lattices. Auxetic additively manufactured truss lattice prototypes can be utilized as reinforcement in cementitious composites to harness this increase in confinement pressure and achieve superior mechanical properties that can be adopted in structural members. The authors study the enhancement of the compressive properties, such as the peak stresses and peak strains, through experiments and finite element computations in cuboid specimens for two different three-dimensional families of metal auxetic architectures, including various geometric configurations. The architectures that were studied include auxetic re-entrant and convex truss lattices utilizing 15-5 PH stainless steel auxetic truss lattices as reinforcement and cementitious mortars in interpenetrating phase composites, delineating the various mechanical behaviors that arise. A comparison with conventional reinforced concrete column designs is presented. The manufacturing of prototype IPC column specimens is showcased using the candidate unit cell architecture that exhibits the most considerable improvement in terms of mechanical properties when compared to a conventional design of a reinforced concrete column. Both cuboid and taller column specimens are discussed and compared. A non-rule-of-mixtures behavior is observed inside the composites, which is exploited to create stronger and more ductile columns in axial compression for future civil infrastructure applications.

Advancements of data-driven methods in computational mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A LARGE LANGUAGE MODEL AND DENOISING DIFFUSION FRAMEWORK FOR TARGETED DESIGN OF MICROSTRUCTURES WITH COMMANDS IN NATURAL LANGUAGE

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ABSTRACT

Microstructure's crucial impact on macroscopic properties is widely recognized, with alloy phase distribution affecting mechanical properties, microfeature precision in MEMS dictating device performance, and cellular arrangement in tissue-engineered scaffolds influencing cell growth and differentiation, among countless other domains of study. While advanced ML-based design and generative AI tools exist to explore the forward and inverse relationships between microstructure and macroscopic behaviors, a substantial knowledge and expertise barrier limits their accessibility and broader application in the field. To address this, we introduce a framework that combines Large Language Models (LLMs) and Denoising Diffusion Probabilistic Models (DDPMs) to streamline the design of complex microstructures for users of all expertise levels in mechanics, materials science, and machine learning. By leveraging LLMs, our framework reduces the expertise barrier, allowing users with diverse backgrounds to specify design objectives in intuitive language. The core of this system is an LLM that interprets these inputs, translating them into actionable directives for a DDPM algorithm. This integration effectively democratizes access to complex design processes, making advanced microstructure design more accessible and adaptable. Central to our methodology are DDPMs, generative models that learn to reverse a Markov diffusion process and have been proven to work exceptionally well in text-conditional settings, enabling the generation of synthetic microstructures with specific, fine-tuned properties. This approach allows the manipulation of microstructure topology within the latent space of the training data, ensuring the generation of realistic and viable designs. Demonstrated using the Mechanical MNIST dataset as a benchmark and extending on the work by Vlassis et al, 2023, our framework highlights the capability of DDPMs in performing the inverse design of microstructures with specific nonlinear properties and in understanding the nonlinear structure-property relationships through natural language commands embedded by the coupled LLM. This is critical for exploring the complex interactions among geometry, topology, and macroscopic properties in materials through a user-friendly text interface. This integration of LLMs and DDPMs aims to introduce a paradigm in microstructure design, combining advanced generative machine learning methodologies under a singular, intuitive interface.

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4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PHYSICS-BASED CRYSTAL PLASTICITY MODEL WITH APPLICATIONS IN SIMULATION OF MICROPILLAR COMPRESSION AND STRENGTHENING EFFECT OF MULTILAYERED COPPER-GRAPHENE NANOCOMPOSITES

George Z. Voyiadjis[1] and Juyoung Jeong[2]*

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ABSTRACT

A new crystal plasticity model based on the dislocation mechanism is developed to study the mechanical behavior of face-centered cubic (FCC) single crystals under heterogeneous inelastic deformation through a crystal plasticity finite element method (CPFEM). The main feature of this work is generalized constitutive relations that incorporate the thermally activated and drag mechanisms to cover different kinetics of viscoplastic flow in metals at a variety of ranges of stresses and strain rates. The constitutive laws are founded upon integrating continuum description of crystal plasticity framework with dislocation densities which is relevant to the geometrically necessary dislocation (GND) densities and the statistically stored dislocation (SSD) densities. The model describes the plastic flow and the yielding of FCC single-crystal employing evolution laws of dislocation densities with mechanism-based material parameters passed from experiments or small-scale computational models. The GNDs evolve on account of the curl of the plastic deformation gradient where its associated closure failure of the Burgers circuit exists. A minimization scheme termed -norm is utilized to secure lower bounds of the GND densities on slip systems. The evolution equations of SSDs describe the complex interactions between two distinct dislocation populations, mobile, and immobile SSDs, relying on generation, annihilation, interactions, trapping, and recovery.

The experiments of a micropillar compression for the copper single crystal are compared to the computational results obtained using the formulation. The physics-based model clarifies the complex microstructural evolution of dislocation densities in metals and alloys, allowing for more accurate prediction.

This work also investigates plastic deformation mechanisms in metal-graphene nanocomposite to demonstrate the strengthening effect of materials through a crystal plasticity finite element (CPFE) model comparing published experimental results. The existing experimental research identified that the two-dimensional shape of graphene, which can effectively control dislocation motion, can significantly strengthen metals. The present study quantified the accumulation of dislocations at the graphene interfaces, leading to the ultra-high strength of the copper-graphene composite. Furthermore, a Hall-Petch-like correlation was established between yield strength and the number of embedded graphene layers.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPLORING FABRIC TENSORS IN DAMAGE AND HEALING MECHANICS OF MATERIALS

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ABSTRACT

The paper presents precise mathematical relationships among the damage tensor, healing tensor, and fabric tensors, serving as a crucial bridge between Damage and Healing Mechanics and Fabric Tensors. A novel fabric-based damage-healing tensor is introduced to enhance understanding. These tensors play a pivotal role in characterizing the micro-structure of materials, enabling the examination of solids with micro-cracks within the framework of Damage and Healing Mechanics. Notably, the theory is applicable exclusively to linear elastic solids.

The explicit derivation of relations encompasses the general case of anisotropic elasticity with anisotropic damage and healing. Extending the applicability, the paper solves four additional cases: isotropic elasticity with isotropic damage, isotropic elasticity with anisotropic damage, plane stress, and plane strain. To illustrate, a numerical example is presented for a specific micro-crack distribution.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING THE MECHANICAL BEHAVIOR OF 3D-PRINTED INCONEL 718 HEXAGONAL HONEYCOMB STRUCTURES: A COMPREHENSIVE STUDY

George Z. Voyiadjis[1], Reem Abo Znemah[1] and Paul Wood[2]*

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ABSTRACT

To fully unlock the creative possibilities offered by 3D printing for metal, it is imperative to comprehend the impact of process parameters and applied heat treatment on the mechanical behavior of complex cellular structures. Specifically, we aim to explore how current optimized printing parameters, involving high speeds within the part's inner space and lower speeds with increased energy input at the part's exterior, interact as individual element thicknesses in these structures approach the submillimeter scale. This comprehensive study endeavors to examine the impact of heat treatment, geometry (element thickness), and load direction on the compressive performance of Inconel 718 (INC718) laser powder bed fused (LPBF-ed) hexagonal honeycomb specimens. Honeycomb samples of different wall thicknesses (0.4 mm, 0.6 mm, and 0.8 mm) and flat sheets of equivalent thickness were printed. The flat sheets were machined into miniature tensile specimens to study the parent material behavior. Subsequently, half of the printed specimens were stress-relieved, while the second half was solution annealed and age hardened. Electron backscatter diffraction tests were conducted to investigate the effects of heat treatment and element thickness on the resulting microstructure. A miniature tensile tester was employed to assess the influence of heat treatment, element thickness, and loading orientation on parent material mechanical behavior. Finally, quasi-static compression tests were conducted along the three perpendicular major axes of the honeycomb samples, evaluating mechanical performance and energy-absorbing characteristics (plateau stress, specific absorbed energy, Ideality, and efficiency) for each study set.

Observations on the stress-relieved samples revealed three distinct microstructure zones across submillimeter element thicknesses, linked to variations in printing parameters and heat field distribution. The percentage contribution of each zone to the overall thickness varied with the element thickness, resulting in a variable parent material behavior. Loading orientation also proved influential. When compressed in the plane of the honeycomb, the studied structures showed excellent energy absorbing characteristics compared to other 3D-printed metallic cellular structures. Stress-strain behavior was bending-dominated in one direction and bending-stretch dominated in the other, with no initial stress peaks. Solution annealing followed by age hardening heat treatment is anticipated to further improve the mechanical behavior and energy absorbing characteristics.

The coupling between element thickness/ orientation and material behavior challenges the conventional analytical models in explaining the mechanical performance of 3D printed cellular structures and requires including it in any optimization process. This research extends beyond the established paradigms, contributing vital insights to the dynamic field of additive manufacturing.

Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACOUSTIC EMISSION-BASED DAMAGE LOCALIZATION: A TIME-FREQUENCY ANALYSIS AND DEEP LEARNING APPROACH

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ABSTRACT

In the construction industry, detecting and localizing structural deterioration is crucial. Acoustic emission sensors are commonly used to identify cracks, but traditional methods relying on time measurements and parameter-based have limitations, especially with inhomogeneous materials. This research introduces an innovative approach using deep learning techniques to enhance crack localization accuracy and automate the process. The proposed method involves capturing signals from acoustic emission sensors, converting them into a time-frequency representation using continuous wavelet transform, and feeding these representations into a specially designed convolutional neural network, AECWT-3DR-Net. This network is trained to locate and predict the three-dimensional coordinates of the crack. Experimental validation on a concrete block with an artificially created crack confirmed the effectiveness and advancements of the proposed method.

Keywords: Damage Localization, Acoustic Emission Sensor, Deep Learning.

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ASSESSING THE PERFORMANCE OF THE CRUMB RUBBER MODIFIED (CRM) BITUMEN CONTAINING WARM MIX ADDITIVES AT REDUCED AGING TEMPERATURES

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ABSTRACT

The primary objective of the study is to minimise the production temperature and ensure the positive performance of crumb rubber modified (CRM) binder using WMA technology. This study attempts to explore the mixing and compaction temperatures of CRM mixtures incorporated with WMA additives. This study also investigates the effects of two different WM additives, one wax based (Sasobit) and another chemical based (Rediset), on the performance properties of CRM asphalt binder due to reduced aging temperature. To determine the production temperature CRM binders incorporated with WMA technology, the newly developed workability approach has been used in this study. From study, it was found that the conventional equi-viscous method does not yield appropriate results for CRM asphalt binders. Workability analysis showed that CRM mixtures incorporated with WMA technology, regardless of dosage and type, exhibit improved workability at all the test temperatures compared to the CRM mixture without WMA incorporation. It was found that the workability approach used in this study was able to quantify the mixing and compaction temperatures for different CRM mixture incorporated with WMA technologies. About 4-13% and 5-22% reduction in mixing and compaction temperatures, respectively, were obtained for different WMA technologies. To study the impact of reduced produced production temperature on aging, the Fourier transform infrared spectroscopy (FTIR) was conducted on CRM asphalt binders to check changes in their chemical composition due to aging. Performance of the WM modified asphalt binders was assessed using indirect tensile cracking test, (IDEAL CT), dynamic creep test, tensile strength ratio test, and bitumen bond strength (BBS) tests. BBS test was conducted using two types of aggregate Siliceous (Granite) and Calcareous (Dolomite). FTIR analysis showed that the addition of WM additives increases the aging resistance of asphalt binder. Test results revealed that the application of Rediset enhanced the fatigue performance as compared to neat and Sasobit modified asphalt binder. On the other hand, Sasobit improved the rutting performance of the binder, whereas the rutting observed to be similar with the addition of the Rediset. It was found that Rediset acts as an antistripping agent, which aids in improving the bond between asphalt binder and the aggregate, even at reduced production temperatures.

Keywords: Crumb rubber, Warm Mix Asphalt, Workability, IDEAL CT, dynamic creep, BBS.

New challenges in instabilities of shell structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NEW XFEM APPROACH FOR THE ANALYSIS OF THIN-WALLED STRUCTURES

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ABSTRACT

Thin-walled beams have many engineering applications. Considering the longitudinal dimension, we propose a new XFEM method with global enrichment functions based upon a coarse 3D solid element mesh. Analytical global enrichment functions are used to provide approximate solution of the beam for deflection as well as for lateral-torsional buckling. To this end we consider vibration modes and buckling modes, including higher order modes. Further, we employ the modification proposed in the stable GFEM approach to obtain a robust numerical behavior.

The resulting model bridges the gap between the Finite Prism Method (FPM), which provides an efficient approximation to beam bending with analytical functions but has also well-known limitations, and a detailed 3D FE model, which can accurately resolve thin-walled structures but is computationally demanding.

The method can be easily extended for beams with non-prismatic cross-sections (e.g., tapered beams) or with perforations, and additionally, one can improve the solution by sectional and/or longitudinal mesh refinements. Moreover, the proposed method enables modelling of different boundary conditions along the beam, such as lateral restraints.

The performance of the model is investigated on several benchmark problems. The results show that the proposed method captures different global and sectional deformation modes including shear-lag and warping of the cross-section, as well as buckling behavior of thin-walled beams subjected to complex loads. Furthermore, convergence studies demonstrate the superior performance of the proposed method as compared to the FPM, and a 3D FE model with a coarse mesh.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENERGY ABSORPTION OF METALLIC KIRIGAMI STRUCTURES

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[1]*University Of Surrey*

ABSTRACT

Kirigami, the Japanese art of paper cutting, can be used to generate complex 3D shapes from 2D sheets via out-of-plane buckling. Kirigami structures can also be highly stretchable and accommodate extremely large strains from common materials, such as aluminium, which admit relatively small strains. The high stretchability of Kirigami makes it an ideal method for energy absorption applications.
We investigate the tensile behaviour of metallic Kirigami structures with different geometrical parameters in the parallel-cut pattern. We combine a reduced-order analytical model with a parametric study, using Finite Element Analysis (FEA), to identify the key geometric parameters, such as distance between successive cutting rows, that control the energy absorption behaviour.

Emerging topology and shape optimization techniques in computational design of materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF ELASTO-PLASTIC STRUCTURES AND MATERIALS

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ABSTRACT

For structures operating within the linear regime, numerical design optimization techniques have proven successful in achieving optimal designs. Simple objectives such as stiffness, eigenfrequency, buckling and peak stress for linear elasticity can now be readily found in commercial finite element software packages. However, less exploration has occurred in the realm of non-linear problems, specifically those involving irreversible material responses and transient loading conditions. In this study, we integrate finite strain viscoplastic and rate-independent plasticity with density-based topology optimization (TO). We assume isotropic hardening and adopt the multiplicative split of the deformation gradient to distinguish between elastic and plastic deformation. To update the design, we employ the gradient-based Method of Moving Asymptotes (MMA), necessitating the calculation of gradients for both cost and constraint functions. Given that the number of design variables (one per element) far exceeds the number of state functions, we opt for the adjoint sensitivity approach. The inherent plastic path-dependence introduces complexity into the sensitivity analysis, leading us to adopt a coupled transient adjoint strategy, effectively transforming it into a terminal value problem. To illustrate our theoretical framework, we design structures and materials optimized for maximum energy absorption and structures that limits the peak plastic work. Our results show that loading rate, loading path, and load magnitude all play important roles in the design of energy-absorbing structures. Furthermore, we will discuss implementation aspects and present results showcasing the successful resolution of large-scale elasto-plastic TO problems.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVERSE DESIGN OF MAGNETO-ACTIVE METASURFACES AND ROBOTS: THEORY, COMPUTATION, AND EXPERIMENTAL VALIDATION

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ABSTRACT

Magneto-active structures can undergo rapid and reversible deformations under untethered magnetic fields. The capability to design such structures to achieve programmable shape morphing in three dimensions (3D) under magnetic actuation is highly desirable for many applications. In this work, we develop a multi-physics topology optimization framework for the inverse design of magneto-active metasurfaces that can undergo programmable shape morphing in 3D under external magnetic fields. These metasurfaces remain planar in their initial configurations and are deformed into complex 3D target shapes. The proposed framework accounts for large-deformation kinematics and optimizes both the topologies and magnetization distributions of metasurfaces in conjunction with the directions and magnitudes of the external magnetic fields. We demonstrate the framework in the design of kirigami metasurfaces, bio-inspired robots, and multi-modal magnetic actuators, and the optimized designs show high precision and performance in achieving complex 3D deformations. We also use a hybrid fabrication procedure to manufacture representative designs and conduct experimental tests to validate their programmed 3D deformations, with results showing good agreement with simulation predictions. We envision that the proposed framework could lead to a systematic and versatile approach for the design of magneto-active metasurfaces for robotics applications.

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DISTRIBUTED STRUCTURAL HEALTH MONITORING OF A FIVE-SPAN BRIDGE

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ABSTRACT

This presentation discusses the structural health monitoring of a five-span concrete box girder bridge in Northern Illinois. The instrumentation involved the installation of distributed fiber optic Brillouin Scattering sensors covering the entire spans of the bridge. Considering that the bridge had a total length of 332 m (1090 feet), approximately 1445 m (4750 feet) of optical fibers were installed to cover and monitor various sections of the bridge. Testing of the bridge involved 15 different load positions over the 5 spans. The load positions were selected based on influence line analysis to create maximum load effects on all the bridge spans. Load tests involved two load steps, with one larger than the other. Loading of the bridge involved using larger commercial trucks with heavy payloads. This presentation will compare the measurements taken three years before the recent measurements pointing at major events causing strain changes in the bridge.

On the mechanics of road and paving materials in the cold, Nordic, and Arctic Regions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPARISON OF CRITICAL ASSESSMENT METHODOLOGIES AND INDEXES OF LOW TEMPERATURE PERFORMANCE OF ASPHALT BINDERS

Di Wang[1], Tewodros Dugasa Gebre[2], Augusto Cannone Falchetto[3] and Fan Zhang[3]*

[1]University of Ottawa
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ABSTRACT

In cold regions, one of the most serious distresses in road infrastructure was initiated caused by thermal damage. In particular thermal crackings in asphalt roads since it is commonly used as paving materials. Therefore, accurately evaluating the performance properties of bituminous materials could eliminate or at least mitigate low-temperature cracking, which is of great importance in improving the durability and sustainability of asphalt pavement. The low temperature response of bituminous mixtures mainly depends on the performance properties of the binder itself. The commonly used Bending beam rheometer (BBR) is a prominent low temperature performance evaluation method, which has also been standardized in many regions. However, such a testing method requires a substantial amount of material, moreover, its testing protocol (including cooling medium and thermal history) may underestimate the stiff properties of asphalt binder at low temperatures. In the recent past, a novel method based on the 4-mm parallel-plate geometry Dynamic Shear Rheometer was proposed as an alternative method of BBR. Based on the PG system, the DSR data were converted to equivalent BBR parameters. Plenty of researchers have attempted to correlate the relationships between BBR and 4-mm DSR with available materials, and good indications and correlations have been generated on the predictability of thermal cracking from 4-mm DSR.

In this present study, the Finnish source asphalt binders were applied to validate and assess the proposed correlations. Five methods and indicators together with six long-term aged asphalt binders (four unmodified and two modified binders) were selected for this purpose. First, three temperatures, -12°C, -18°C, and -24°C, were used for the BBR test on all these six asphalt binders, and PG indicators (Tc,s, Tc,m, ΔTc, and PG) were calculated based on the experimental results. Meanwhile, 4-mm DSR tests were conducted on all materials. Next, the related rheological parameters were calculated based on the existing methods, and the PG indicators were computed relying on the correlations. Finally, the DSR computed-based and BBR experimental-based parameters were compared and discussed. However, poor correlations were realized among all five existing methods, no method can be considered as a universal model. This may be attributed to the limited available materials and different testing protocols (sample preparation and thermal history). Therefore, a wider range of materials should be tested to generate a better-correlated model.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPTIMIZED FILTER DESIGN FRAMEWORK FOR PHASE-BASED VIDEO MOTION ESTIMATION WITH CONTROLLED ERROR DISTRIBUTION

Haifeng Wang[1]*

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ABSTRACT

Vision-based motion extraction, known for its non-invasive approach, efficiency, and high spatial resolution, has garnered considerable attention in recent research. This technique, employing camera videos, capitalizes on the capability of pixel sensors to discern 256 or more brightness levels, thereby enabling sub-pixel accuracy in motion estimation. To achieve this, interpolation-based and gradient-based methods have been developed. Phase-based motion estimation, in particular, stands out due to its ability to integrate a broader pixel array, significantly reducing noise sensitivity, and thus has become a key area of research.

Despite its advantages, the accuracy of phase-based motion estimation is heavily dependent on the filter choice and the characteristics of the target object. Employing a standard filter for objects with varied features often leads to inconsistent estimation errors. This issue is especially pronounced in videos containing multiple distinct features and can adversely affect the effectiveness of subsequent response-based analytical techniques. In response to this challenge, we introduce a novel feature-based optimization filter design framework. This framework is tailored to optimize error distribution, with a specific focus on the mean and standard deviation. It utilizes the distinct features of the target region to calculate the error distribution for various filters, enabling the selection of the most optimized filter.

Our framework facilitates the prediction of expected error statistics with enhanced precision, thus improving the accuracy of follow-up response-based analyses. The experimental findings confirm the efficacy of our method in achieving controlled error distribution in motion estimation, which significantly increases the reliability of response-based studies.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PIXEL-LEVEL UNSUPERVISED ANOMALY DETECTION FOR TILE SPALLING IN NOISY STREET VIEW IMAGES

Hai-Wei Wang[1] and Rih-Teng Wu[1]*

[1]National Taiwan University

ABSTRACT

The facades of architectural structures frequently undergo surface deterioration, exemplified by tile spalling resulting from the combined effects of aging and environmental conditions. The detachment of such spalled fragments poses significant safety concerns for pedestrians and vehicles on adjacent sidewalks. In recent years, the inspection of exterior walls heavily relies on visual assessments conducted by skilled engineers, a process characterized by its labor-intensive nature and time-consuming requirements. Conventional deep learning methods in this domain often employ a supervised training approach, wherein the model learns representations of spalling and identifies affected areas. However, the supervised approach demands large amounts of labeled data, presenting a challenge in our case due to the lack of spalling images and the variable spallings difficult to label. In this study, we propose an unsupervised learning methodology to alleviate the label-intensive constraints of conventional deep learning approaches. Drawing inspiration from anomaly detection principles, our model is trained on spalling-free building samples, enabling it to learn patterns and data distributions of normal datasets. Consequently, when confronted with a spalling sample, the model identifies anomalous patterns indicative of tile spalling. Furthermore, we have implemented mechanisms in the training process to lower the impact of real-world image noise, such as vegetation or traffic signs, redirecting the model's attention towards the buildings and enhancing overall performance. Our approach relies solely on unlabeled normal data, thus addressing the issue of label-intensity in conventional deep learning methods. This advancement contributes to the efficiency and scalability of spalling detection methodologies, offering an avenue for more label-efficiency inspection processes in the realm of architectural maintenance and safety.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INNOVATIVE LATCHED MASS DAMPER FOR VIBRATION CONTROL INSPIRED BY WAVE ENERGY CONVERTER

Hao Wang[1] *and Songye Zhu*[1]

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ABSTRACT

Traditional passive dampers are sensitive to frequency modulation and difficult to achieve ultra-low frequency modulation. Ultra-low frequency vibrations are common such as vibrations of super-high buildings and floating energy infrastructures. Latching control is a phase optimization method applied in wave energy converters (WECs). Inspired by the latching control of WEC, this paper proposed the latched mass damper (LMD) and three different control strategies for ultra-low frequency vibration control. The LMD can directly extend the periods to match well with the long-period (low frequency) vibrations by introducing the latching forces. First, the theoretical model of WEC and LMD is established and analyzed. Then, the dynamic performances of LMDs with different strategies are compared. Next, the feasibility of latching control in LMD is verified by a proof-of-concept experiment. Furthermore, a case study is carried out based on the 76-story building subject to the across-wind loads benchmark model. The results indicate that the proposed LMD and strategies for vibration control are feasible. The proposed latching control mechanism and strategies can provide an innovative solution for improving the efficiency of high-frequency detuned dampers, designing of long-period dampers with limited stroke spaces, and adaptive semi-active dampers in the future.

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PROBABILISTIC ASSESSMENT OF THE LIQUEFACTION POTENTIAL EVALUATION BY CONSIDERING SPATIAL VARIABILITIES OF GEOLOGICAL AND GEO-PROPERTY MODELS

Wan-Ying Chien[1], Yu-Chen Lu[1], Hui Wang[2], Jia-Jyun Dong[1] and C. Hsein Juang[1]*

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ABSTRACT

Earthquake-induced soil liquefaction can cause enormous life and economic losses. The liquefaction potential map plays a significant role in liquefaction hazard assessment, control, and mitigation, as it can be used to visualize the risk and facilitate easy and effective communication among different stakeholders. Most traditional regional liquefaction potential maps are interpolated from the evaluated liquefaction potential index (PL) at each borehole, which renders the deterministic liquefaction hazard level but seldom takes the spatial variabilities of geological configuration and geo-property into consideration. However, these spatial variabilities may bring doubts about the accuracy and applicability of the traditional regional liquefaction map.

To account for the uncertainties that exist in the geological and geo-property models, this paper presents a probabilistic assessment framework of the liquefaction potential evaluation by considering both uncertainty sources. A case history in the Taipei Basin, Taiwan is selected as the demonstrated example. Dozens of SPT borehole logs were collected at this site. First, the 3D coupled geological and geo-property random field method is adopted to simulate a series of geological models and their derived geo-property (normalized SPT-N, N1,60cs) models. Then, a series of spatial distributions of the safety factor against liquefaction (FL) were obtained by substituting the geological and geo-property models into the simplified method. Finally, the mean, uncertainty, and confidence interval of PL could be further calculated based on the FL models. Additionally, this paper establishes the quantified correlation between the geo-property model uncertainty and the PL uncertainty. A liquefaction potential (FL) map with improved reliability and confidence level by considering spatial variabilities of geological and geo-property models is provided.

Mechanics of granular materials: Modeling and characterization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT MODELING APPROACHES FOR LATTICE DISCRETE PARTICLE MODELS

Jiajia Wang[1], Jan Vorel[2], Wouter Botte[1] and Roman Wan-Wendner[1]*

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ABSTRACT

Reliable and computationally efficient models are essential in the design, optimization, or control for various application domains. However, simulating the mechanics of granular materials often becomes impractical in terms of computational cost. Finding convenient trade-offs between the accuracy and calculation time of such computational models is a prominent research focus. This paper employs a state-of-the-art Lattice Discrete Particle Modeling (LDPM) to simulate concrete at the coarse aggregate level, streamlining the number of tessellation facets attached to the edges. Whereas the original formulation of LDPM involves 12 Facets for each basic four-particle tetrahedron, this study introduces a simplified discretization approach for LDPM, incorporating either 6 Facets and Edge-based interactions or 12 Facets and Edge-based interactions. The goal is to significantly reduce computational costs while maintaining accurate predictions of concrete fracture behavior. Uniaxial compression and three-point bending mechanical models are employed for simulations, exploring various combinations of 6 Facets and Edge-based interactions or 12 Facets and Edge-based interactions. Mechanical behaviors and computational costs are obtained for different combinations, and statistical analysis is performed to identify the most efficient and accurate model. The results indicate that modeling approaches incorporating Edge-based, 6 Facets and 12 Facets interactions substantially reduce computational costs, providing similar results in terms of structural response as the original LDPM based on 12 Facets. This research paves the way for advancing the utilization of LDPM in concrete mechanics simulations.

UNLOCK CO2 SEQUESTRATION POTENTIAL OF CONCRETE THROUGH A BIOMOLECULE-REGULATED CARBONATION PROCESS

Xiaodong Wang[1] *and Jialai Wang**[1]

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ABSTRACT

Concrete with ordinary Portland cement (OPC) as the main binder is the most widely used construction material in the world. On one hand, the production of OPC is highly energy-intensive and responsible for approximately 8% of global CO2 emissions. On the other hand, the massive volume of concrete used in construction each year offers one of the largest sinks for CO2 through a mineral carbonation process. However, existing technologies can only sequestrate very small amount of CO2 due to the inherited limitation of the existing carbonation methods. The major objective of this study is to increase the amount of CO2 sequestrated in concretes by at least one order of magnitude higher than existing technologies and drastically increase the compressive strength of the produced concrete. To this end, a new pathway to sequester CO2 in concrete is proposed through a biomolecule regulated carbonation (BioCarb) method. In this method, cement slurry is first carbonated through bubbling CO2 under the regulation of some biomolecule. The biomolecule functions as a chelating agent to facilitate the carbonation of the cement slurry, a hydration suppressor to allow more complete carbonation, and a dispersant and polymorph controller of the produced CaCO3 to disperse metastable CaCO3 nanoparticles produced in-situ by the carbonation. The resulting carbonated slurry is then mixed with other ingredients to make concrete. Testing results suggest that this method can store at least 15lb-CO2 in one cubic yard of concrete, which is 30 times more than existing technology. More importantly, the compressive strength of the concrete can be enhanced over 20%, drastically reducing the CO2 emission of the produced concrete.

NOVEL PHASE CHANGE MATERIAL MICROCAPSULE FEATURING AN INORGANIC SHELL AND A BIO-INSPIRED SILICA COATING FOR STRUCTURAL CEMENTITIOUS MATERIALS

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ABSTRACT

Phase change material (PCM) microcapsules offer a promising approach for integrating PCM into building materials for efficient thermal energy storage. This study presents the development of a novel PCM microcapsule specifically designed for incorporation into cementitious materials. The microcapsule consists of a low-cost PCM core derived from vegetable oil by-products and a durable inorganic shell made from cenosphere, a hollow fly ash generated from coal burning power plants. A novel process is developed to apply a silica coating to these cenosphere-based PCM microcapsules (CPCM), resulting in bioinspired-silica-coated CPCM microcapsules (BCPCM). This coating process draws inspiration from marine microorganism-based silica production and utilizes low-cost sodium silicate as a precursor, enabling eco-friendly and cost-effective manufacturing at ambient temperature and mild pH conditions. The morphology, chemical stability, and thermal properties of the BCPCM along with its thermo-mechanical performance in cementitious composites were comprehensively analyzed. Experimental results demonstrate successful silica deposition on BCPCM, leading to enhanced latent heat properties of the produced BCPCM. With the silica coating, BCPCM exhibits a 50°C delay in thermal decomposition compared to CPCM, enhancing fire resistance and preventing premature PCM leakage of the microcapsule. The bioinspired silica coating effectively restores over 10% of the strength loss for each percent increase in CPCM incorporated into the mortar. The thermal performance experiments reveal that increasing the BCPCM content reduces temperature peaks and rates of temperature increase, indicating an improved capacity for thermal energy storage. This new PCM microcapsule provides a cost-effective solution to integrate thermal energy storage to cementitious material, as evidenced by that over 30% aggregates (in volume) can be replaced by the microcapsule without drastically loss of strength.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BIO-INSPIRED SILICA COATING FOR STEEL FIBERS

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ABSTRACT

Concretes are most used construction materials. They can be considered as a three-phase material, the cement matrix, reinforcements and interfacial transition zones (ITZ) between the cement matrix and reinforcements. Various materials have been used as reinforcements for concretes, including coarse/fine aggregates and various fibers (steel, glass, carbon, polymers, natural fibers). The ITZ plays a critical role on the mechanical properties and durability of the concrete. This invention proposes a low-cost, eco-friendly, bio-inspired method to coat a thin layer of silica on the surface of steel fibers so that the bond strength between the fibers and the cement paste can be significantly improved, leading to higher strength and durability of the produced concrete.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCED INTERNAL CURING FOR UHPC USING CARBAMIDE SOLUTION CARRIED BY PERFORATED CENOSPHERES

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ABSTRACT

This paper proposes an internal carbon-mineralization method, using carbamide solution carried by perforated cenospheres (PCs), to produce a synergistic curing effect for UHPC based on internal curing, where PCs was added as an alternative to part of the fly ash of UHPC. Experimental investigations show that the addition of PCs with carbamide solution concentrations ranging from 0.5% to 3.0% sustained the internal relative humidity at high levels, effectively mitigated the autogenous shrinkage, and slightly enhanced the 28d compressive strength of the produced UHPC. Very small amount of the carried carbamide solution by PCs was released through the dynamic and vigorous mixing processes of UHPC, while most of it was released due to the changes in the internal relative humidity of UHPC. As a result, the presence of carbamide in the hydrating system of UHPC consumed partial hydrated Ca(OH)2 for internal carbon-mineralization. The produced fine CaCO3 can thus densified the microstructure and strengthened the micro-mechanical properties of UHPC, along with internal curing effect. A comparison analysis of PCs for internal carbon-mineralization with other water reservoirs for internal curing for UHPC demonstrated the features of PCs of high-efficiency and positive role in enhancing the performance of UHPC. Moreover, the mechanism of internal carbon-mineralization was discussed and revealed.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BUCKLING ANALYSIS OF MWCNT AND FUNCTIONALLY GRADED CARBON NANOTUBE REINFORCED COMPOSITE QUADRILATERAL PLATE

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ABSTRACT

The structural instability of multi-walled carbon nanotubes (MWCNTs) has captured extensive attention due to the unique characteristic of extremely thin hollow cylinder structure. This presentation firstly investigates the axial buckling behavior of MWCNTs with the length-to-outermost radius ratio less than 20 within the framework of the Donnell shell theory. Subsequently, from nanoscale extending to macroscale structures of functionally graded CNT reinforced composite plates (FG-CNTRC), the thermal vibration and buckling of FG-CNTRC quadrilateral plate are considered including four distributions of reinforcements along the thickness direction: uniform distributions (UD), FG-V, FG-O and FG-X. The corresponding effective material properties including Young's modulus, mass density, Poisson's ratio and thermal expansion coefficients are estimated by the rule of mixture with respect to the CNT efficiency parameters based on the size-dependence principle. The first-order shear deformation theory (FSDT) considering thermal effects is employed. Based on Hamilton's principle and moving least square (MLS) approximation, the discrete governing equations for the vibration of FG-CNTRC plate are derived. The free vibration of regular and irregular plates with and without the temperature effect are considered, and the corresponding natural frequencies and mode shapes are obtained as an eigenvalue problem. The stability analysis of uniaxial and biaxial mechanical and thermal buckling is also conducted. Finally, the effects of volume fraction, distribution pattern, geometrical characteristics and temperature on the buckling behavior of CNTRC quadrilateral plate are discussed in detail.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

APPLICATION OF AN IMMERSED BOUNDARY METHOD TO GENERATE BOUNDARY LAYER TURBULENCE AND NON-UNIFORM WIND FIELDS

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ABSTRACT

Large-eddy simulations of wind engineering problems frequently rely on a combination of artificial turbulence generation and a rough wall function on the ground surface to generate a neutral surface layer flow. This approach may fall short when the aim is to capture non-standard wind conditions. Examples range from modeling the roughness sublayer for simulations of low-rise buildings to modeling profiles that deviate from the typical log-law shape or modeling unsteady events such as downbursts. To address these challenges, this study explores the use of an Immersed Boundary Method (IBM) to simulate the interaction between the wind flow and a combination of roughness elements, spires, or louvers positioned in the flow development section of the computational domain. Similar to wind tunnel experiments, the upstream configuration of these elements can then be optimized to reproduce a specific target wind field in the test section of the domain. We employ a direct forcing IBM, implemented in an otherwise body-fitted computational fluid dynamics (CFD) code. The implementation is tested on two set-ups: one with roughness elements that will generate a roughness sublayer for low rise building applications, and one with louvres that generate a non-standard mean velocity profile. For both cases, the IBM flow predictions in the test section downstream of the flow development section are compared against results obtained using body-fitted meshes for the same configurations. For the cases where data is available, comparative analysis with wind tunnel experiments is used to further determine the method's capability to accurately simulate a range of ABL wind conditions. The findings demonstrate the method's promising capabilities for simulating boundary layer flows with a range of mean velocity profiles and turbulence characteristics, simplifying the set-up of numerical analysis of a wide range of wind engineering flows without compromising on computational efficiency.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL CHARACTERIZATION AND COMPUTER VISION-BASED DETECTION OF PITTING CORROSION ON STAINLESS STEEL

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ABSTRACT

Pitting corrosion is a prevalent form of corrosive damage that can weaken, damage, and initiate failure in corrosion-resistant metallic materials. For instance, 304 stainless steel is commonly utilized in various structures (e.g., miter gates, heat exchangers, and storage tanks), but is prone to failure through pitting corrosion and stress corrosion cracking under mechanical loading, regardless of its high corrosion resistance. On a microscopic scale, pitting corrosion occurs when an anion with high permeability (typically chloride) passes through the passivating oxide layer on the exterior of stainless steel. Once implanted, the ions will concentrate on local anodic regions and bore holes into the bulk material, depositing byproducts around cathodic regions. The pit growth typically follows a sigmoidal trend with an initial high growth rate during nucleation, followed by an eventual saturation limit, which will ultimately lead to material failure. Evidently, pitting corrosion damage can significantly compromise structural safety and reliability. However, current techniques for evaluating and detecting pitting corrosion (e.g., visual inspection, profilometry, metal penetration, and eddy currents) are still relatively limited and ineffective. Therefore, in this study, to better understand the pitting corrosion damage development under different conditions, accelerated corrosion experiments were designed to generate pits on 304 stainless steel specimens with and without mechanical loading in a consistent and controllable manner. The pit morphology (i.e., depth and surface opening area) development over time was characterized using a laser scanning system. Image processing techniques were used to characterize the statistical features of pit size and spatial distribution based on optical images of corroded specimens. In addition, to achieve scalable and non-destructive assessment of pitting corrosion conditions, convolutional neural network-based computer vision algorithms were adopted and implemented for identifying the existence of pit damage on the steel specimens. Overall, this study contributes a novel experimental technique of high controllability for generating pitting corrosion damage with and without mechanical loading, previously unavailable data on pit morphology evolution under different conditions, and computer vision algorithms for efficiently detecting pit damage on structural members.

LONGITUDINAL MULTIPLE PRESENCE OF TRUCKS ON CONTINUOUS BRIDGE SPANS

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ABSTRACT

Truck load has a major impact on the safety and service performance of highway bridges. In design and evaluation, multiple trucks simultaneously present on the same bridge forms the controlling load case. The magnitude of these controlling load cases depends on various factors such as truck weight and configuration, average daily truck traffic, bridge span length, and number of lanes. Current AASHTO LRFD and LRFR provisions provide guidelines on quantifying the multiple presence of trucks in conjunction with standard truck weight and configuration. However, the quantification is uncultivated, and yields nonuniform bridge safety. This presentation focuses on the multiple presence of trucks loading in the same lane(s) of continuous span bridges. Trucks' longitudinal multiple presence behavior was studied through an unprecedentedly large number of high-quality weigh-in-motion data gathered in eight states across the US. A new approach to analyzing trucks in platoons was developed. The results suggest lower longitudinal multiple presence factors for highway bridge evaluation and design for a more-uniform structural safety and performance.

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Advances in modeling wind and its effects on the built environment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EVALUATION OF RANS MODELING OF URBAN WIND AND TEMPERATURE FIELDS USING OPENFOAM FOR UNCERTAINTY QUANTIFICATION

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ABSTRACT

OpenFOAM underpinsthe foundational numerical framework for the Urban Environmental SMART Sustainable Solutions' (UES3) street-scale numerical modeling component of Community Research on Climate and Urban Science(CROCUS). Associated developments seek to resolve urban form, urban fabric, and urban functionality at high resolution, the final goal being to serve as a digital twin for the City of Chicago. To this end, meter-scale computational fluid dynamics simulations are being performed with multi-physics support using downscaled mesoscale simulation datasets for real-case comparisons, thus melding simulations and observations at the street level. Dynamical Processes are modeled using Reynolds-averaged (i.e. RANS) variables through different turbulent parameterizations, and the results are evaluated against both large eddy simulations (LES) and field measurements conducted for CROCUS measurement sites. RANS simulations are performed with larger time steps and permit coarser grids than LES, and considers both the variable mean and its second-order moments, which allow evaluation of model performance and forecast uncertainties with much cheaper computational costs compared to LES. In the study afoot, uncertainties are evaluated by comparing RANS results with LES ensemble results and field measurements. Inverse modeling of mean fields is also attempted.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECTS OF WALL INCLINATION ON ELEVATED STRUCTURES SUBJECT TO BREAKING WAVES: A MULTIPHASE SPH NUMERICAL EXPLORATION

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ABSTRACT

Due to the increasing probability of extreme weather events, future coastal structures will need to endure higher waves and sea levels, and also short-duration impact pressures from breaking waves. These impact forces can be 10 to 50 times greater than nonbreaking waves and may result in structural failure. The complicated interaction between water and air during wave breaking makes such phenomena difficult to explore numerically and often relies on experiments, which can be expensive, time consuming, and challenged by scaling laws. Meshless smoothed-particle hydrodynamics (SPH) can overcome traditional numerical and experimental difficulties in modeling breaking waves. Unlike traditional Eulerian methods, in SPH fluids are modeled as particles with their trajectory calculated via the discretized Navier-Stokes equations using a kernel function. SPH is therefore well suited for highly nonlinear and deformable flows where air and water interactions at the free surface can be simulated without special treatment.

In this research, we explore the influence of front wall inclination on the pressures and forces induced by wave breaking on an elevated structure. Multiphase (water-air) SPH was used to examine a typical two-story building 6 m high and 10 m long with three different frontal wall inclinations (positive/negative 15 degrees and vertical) impinged by a single breaking wave propagating landwards (left-to-right). Four different levels of building elevation were considered: (1) on-grade (bottom of structure in contact with the ground), (2) semi-submerged (negative air gap), (3) still water level (zero air gap), and (4) fully elevated (positive air gap). Results show that relative to a vertical surface, both positive (clockwise) and negative (counterclockwise) front wall inclinations altered breaking wave pressures depending on the structure's position relative to the still-water level (SWL). When the bottom of the structure is located below the SWL, positive inclination decreased breaking wave loads by up to 21percent, while a negative inclination may result in 50 percent higher pressure maxima. However, for a structure elevated above the SWL (positive air gap), negative and positive inclinations witnessed reductions to the pressure maxima of 35 percent and 10 percent, respectively, when compared with a vertical surface [1].

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SOURCE LOCALIZATION WITH 1D METAMATERIAL ARRAYS FOR ACOUSTIC APPLICATIONS

Weidi Wang[1], Shayan Razi[2], Arghavan Louhghalam[1], Mazdak Tootkaboni[2] and Alireza Amirkhizi[1]*

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ABSTRACT

This work aims to develop novel approaches for acoustic source localization using mechanical metamaterials and their rich dynamic behaviors. Exploiting the dispersion characteristics of metamaterials allows for selective activation of vibrational modes in response to a predefined range of incident wave angles. A 1D finite-sized metamaterial array embedded in water environment is designed as the sensor material and analyzed through the acoustic-solid multi-physics setup. The local resonance modes create multiple so-called optical branches in the eigenfrequency band. These resonance modes can be accessed and activated when the oblique incident wave possesses a certain combination of frequency and wavevector, thereby providing angle-selective behavior near these points in the frequency-wavevector parameter space, unlike the plain spatially harmonic responses provided by traditional homogeneous materials. The scattering response of this periodic metamaterial is then evaluated by a frequency domain calculation with a plane incident wave from varying angles. Using the eigen-modes of the micro-structure as the signal processing kernel, a beamformer model is trained, whose output is shown to be maximized only when the incident angle shares the same wavevector component with the eigen-mode at the operating frequency. Additionally, the sidelobe levels are substantially suppressed. Such an approach shows strong potential for enhanced angle detection, and has expanded application reach of design optimization with phononic crystals and low frequency locally resonant metamaterials.

Objective resilience: Multi-scale resilience measures for electric power networks in climatic hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CLASS FRAGILITY MODELS OF TRANSMISSION TOWERS FOR REGIONAL ANALYSIS OF TRANSMISSION SYSTEMS UNDER HURRICANES

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ABSTRACT

Power transmission systems constitute interconnected networks that cover very large regions and are vulnerable to natural hazards, hurricanes in particular. Lattice steel towers (also known as transmission towers) are commonly used as the support structures in transmission lines and are prone to damages under strong winds. For regional risk and resilience analysis of transmission systems under hurricanes, class fragility models that account for the structure-to-structure uncertainties inherent to a portfolio of transmission towers (in addition to the load uncertainties and within-structure uncertainties) are urgently needed. To fill this gap, this study presents the development of class fragility models for transmission towers by addressing three major challenges.

First, a classification scheme for transmission line support structures is proposed, using structural characteristics (instead of electrical characteristics) that are suitable for the purpose of structural fragility analysis. Second, key design parameters (such as span length) that cause the structure-to-structure variability are identified and are used to characterize the structure-to-structure uncertainties within the interested portfolio of transmission towers. Third, physics-based surrogate models of panel components are developed, which not only facilitates the modeling and analysis of portfolios of transmission towers but also simplifies the uncertainty treatment by condensing modelling parameters. The methodology is demonstrated using the Florida transmission line inventory, where the class fragility models are derived with propagating all three sources of uncertainties. Moreover, a comprehensive sensitivity study is conducted to investigate the significance of the various sources of uncertainties.

EXPLORING THE MICROTEXTURE-EFFECTIVE PROPERTY RELATIONSHIP VIA A MACHINE-LEARNING ASSISTED DATA-DRIVEN APPROACH

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ABSTRACT

The exploration and advancement of fracture-resistant materials hold substantial implications for various engineering disciplines, such as civil, mechanical, aerospace, and others. This presentation introduces a model designed to simulate fracture behavior in heterogeneous materials using an innovative hybrid energy-based approach. The methodology incorporates the potential-of-mean-force (PMF) formulation of the lattice element method (LEM) and directly applies Griffith's fracture criteria [1]. The subsequent application of this approach involves assessing the macroscopic response of random porous materials under external loading. Through a statistical analysis of numerous realizations of two-phase porous materials, we establish a correlation between microstructural properties and macroscopic response. This involves defining and exploring a diverse set of geometric descriptors that characterize micro-texture, including porosity and its local variability, modes of autocorrelation functions in random media, and various graph-theoretical features describing the connectivity of the pore network. With a focus on Bayesian machine learning techniques, particularly Bayesian Additive Regression Tree (BART), we leverage these methods to develop predictive tools for the macroscopic response of porous materials. Furthermore, our study places special emphasis on feature selection through BART to identify the key dominant features significantly impacting the elastic and fracture properties of the materials under investigation. This enables an effective prediction of material performance with reduced computational demands.

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Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

N-ADAPTIVITY: A NEURAL NETWORK ENRICHED PARTITION OF UNITY FOR SOLVING BOUNDARY VALUE PROBLEMS BASED ON POTENTIAL ENERGY MINIMIZATION

Jonghyuk Baek[1]*, Yanran Wang**[2] *and Jiun-Shyan Chen*[2]

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ABSTRACT

This study introduces a novel neural network-enriched Partition of Unity (NN-PU) approach for solving boundary value problems. Motivated by NN-RKPM [1, 2], this NN-PU method employs neural network (NN) enrichment functions, driven by NN-based potential energy minimizations, as extrinsic bases to the background approximations under the Partition of Unity (PU). The local feature characteristics are discovered by NN blocks at the offline stage, forming the NN basis functions. The feature-encoded block-level neural networks are designed to increase sparsity and interpretability of the NN architecture. At the online computation of problems with similar features, each pre-trained feature-encoded NN sub-block targets a distinct local feature as the enrichment of the background PU approximation. The proposed NN-PU approximation and feature-encoded transfer learning forms a model adaptivity framework, termed the neural-refinement (n-refinement). Demonstrated by solving various elasticity problems, the proposed method offers accurate solutions while notably reducing computational resources compared to conventional h- and p-adaptive refinements in the mesh-based methods.

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Geometries & design: Opportunities for sustainable construction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INCLUSIONS GOVERN THE MECHANICAL DEVELOPMENT OF CEMENTITIOUS MATERIALS

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ABSTRACT

In order to address the issue of global warming caused by carbon emissions, various industrial wastes have gained wide popularity in the construction materials market due to active pozzolanic and superior physical properties. However, significant shrinkage and slow strength development render the interface between rock particles and the mortar matrix vulnerable to delamination, ultimately imposing an adverse effect on the development of mechanical properties of cementitious materials. To enable the incorporation of alternative cements and aggregates in concrete, this study calculated the stress distributions caused by mortar shrinkages and identified delamination between rock particle and mortar matrix based on Drucker-Prager failure criterion. Further, a systemic experimental study was carried out to observe the length changes in different cementitious mortars during the early hydration period. Ultimate compressive and tensile strength tests were conducted on cylinder samples after 28 days, which not only offered insights into the mechanical performances of various cement-based materials, but also provided crucial inputs for the proposed theoretical model. A parameter sensitivity study was implemented to explore the effects of rock fractions and particle sizes on delamination occurrences. The results offer valuable suggestions for designing key material and geometric parameters that exhibit a crucial role in controlling the mechanical performance development of concrete materials.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MODELLING OF CONCRETE SHRINKAGE AT MESOSCALE IN A MULTI-PHYSICS FRAMEWORK

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ABSTRACT

The durability and long-term performance of concrete structures are intrinsically linked to their resistance against shrinkage-induced effects. Drying processes in cement-based composites create moisture gradients, leading to non-uniform shrinkage and surface cracks. Studying this intricate mechanical behavior under diverse environmental conditions demands numerous investigations, ideally suited for numerical analysis. This study introduces a mesoscale Multi-physics Lattice Discrete Particle Modeling (M-LDPM) simulation framework to investigate the shrinkage behavior of concrete. The coarse aggregates can be simulated in discrete particles within the volume of concrete randomly by LDPM, to capture the geometrical definition of the concrete meso-structure. In this presentation a new formulation is proposed to distinguish the behavior of non-reactive aggregates from reactive mortar. Another component within M-LDPM is the Hygro-Thermal-Chemical (HTC) model, which plays a vital role in characterizing ongoing curing processes and accounting for heat- and moisture-induced eigenstrains of the reactive mortar. Calibration and validation of the numerical model rely on a series of concrete shrinkage experimental datasets from the existing literature. The results show an excellent agreement between numerical predictions and experimental data, demonstrating significant enhancements in spatial variability and crack formation compared to simpler formulations without increased computational burden. This simulation framework offers a powerful tool to examine the long-term mechanical behavior of concrete structures under diverse environmental conditions, offering valuable insights for improving durability and design considerations.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SINUSOIDAL HELICOIDAL ARCHITECTURE WITH NONPLANAR LAYERING OF FILAMENTS IN ADDITIVELY MANUFACTURED CEMENTITIOUS MATERIALS

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ABSTRACT

The adoption of additive manufacturing of cementitious materials empowered the flexible shaping of external forms and the internal architecture of structural elements. The application of internal filament architectures enables the production of structural elements with unique and tailorable mechanical properties. An effective strategy for designing architectured cement-based materials involves drawing inspiration from nature, particularly biological composites celebrated for their exceptional attributes of high impact resistance and damage tolerance. The sinusoidal helicoidal architecture found in the dactyl club of the mantis shrimp stands out as a notable example of bio-inspired design. During predatory interactions, the impact region of the mantis shrimp's dactyl club, equipped with a unique sinusoidal helicoidal architecture, demonstrated exceptional resistance to extremely high compressive stresses, effectively withstanding the intense forces generated during shell-breaking actions. This presentation will cover the development of 3D-printed concrete (3DCP) specimens featuring nonplanar layering of filaments and sinusoidal helicoidal architectures aimed at improving the mechanical performance of 3DP concrete under compressive loading. The approach to developing the nonplanar layering of filaments in 3D printed concrete will be highlighted, and the influence of this novel architecture on selected mechanical properties of 3D-printed concrete specimens will be discussed.

A DUAL RANDOM LATTICE MODEL FOR THE SIMULATION OF THE TIME EVOLUTION OF BACKWARD EROSION PIPING

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ABSTRACT

Backward erosion piping (BEP) has long been recognized as a significant factor contributing to failures in geotechnical flood protection infrastructure. Despite its relevance, the lack of numerical models for the simulation of the phenomenon has hindered comprehensive understanding and accurate predictions of this highly localized and temporally dynamic phenomenon. This study introduces a novel Dual Random Lattice Modeling (DRLM) framework designed for three-dimensional simulations of BEP, with particular attention devoted to its temporal evolution. The framework incorporates two key innovations: (1) a novel flow energy-based constitutive relationship for time-dependent soil erosion based on the theory of rate processes (Wang et al., 2024), and (2) an algorithm for calculating coupled erosion-induced degradation on dual lattices, ensuring accurate computation of the 3-D hydraulic gradient field. Differently from available semi-analytical approaches, the proposed erosion law is grounded in fundamental granular physics, enhancing its applicability across diverse soil conditions. Moreover, the discrete and spatially random nature of DRLM makes it well-suited for simulating highly localized processes like BEP (Fascetti & Oskay, 2019). The framework's capabilities are evaluated through comparisons with experimental observations (Robbins et al., 2018), demonstrating good agreement in topological distribution of erosion paths, pipe progression velocity, and evolution of local gradients. The DRLM approach is proven to be the first framework capable of simultaneously capturing the three-fold features essential for accurate BEP simulation in geotechnical infrastructure.

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Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NON-PARAMETRIC DIRECTIONAL ENVIRONMENTAL CONTOURS: A METHOD FOR ESTIMATING BRIDGE DESIGN LOAD COMBINATIONS OF WIND AND TEMPERATURE

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ABSTRACT

In recent times, there has been a notable surge in the construction of super-span cable-supported bridges. The continuous growth of the bridge span significantly increases the proportion of environmental load effects within the overall effects. Reassessing the design wind and temperature load combinations from a reliability perspective is essential to guarantee the structural safety of super-span bridges. The environmental contour (EC) method is a representative inverse reliability technique for estimating design loads linked to a given reliability index for engineering structures. An EC defines a set of all possible design points to be explored to find the maximum structural response associated with a target exceedance probability. The point on the EC with the extreme response determines the design environmental load combination.

In accordance with the principles of the EC method, this study introduced a non-parametric directional environmental contour method (NP-DECM). The NP-DECM was designed to find the directional environmental load combination (here, it refers to the wind and temperature loads) associated with the target reliability for the design of super-span bridges. Using the inverse Rosenblatt transformation, the directional ECs were constructed by mapping the points on ECs from the standard normal space to the true physical space based on the joint probability distribution (JPD) of the environmental variables. Notably, the JPD for wind direction, wind speed, and temperature adheres to a circular-linear-linear configuration, given the circular nature of the wind direction variable [1]. Two non-parametric methods were proposed to obtain the aforementioned JPD: the kernel density estimation-based model and the Bernstein copula-based model. A comprehensive evaluation of the proposed approach was conducted through a case study of the Changtai Yangtze River Bridge, a cable-stayed bridge with the largest main span of 1176 m in the world. Through this case study, the design wind and temperature load combinations were determined, with a specific emphasis on different wind directions. The results revealed substantial variations in the load combinations, underscoring the significance of accounting for diverse wind directions in the design process.

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Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STRUCTURAL DAMAGE DETECTION USING PHYSICS-INFORMED DOMAIN ADAPTATION

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ABSTRACT

Structural damage detection is a crucial aspect of structural health monitoring. Unsupervised anomaly detection can predict the structure's state as either healthy or damaged, but it may face challenges in damage localization. In contrast, supervised damage detection can localize the damage when the damage diagnosis model is trained with the data from a finite element model (FEM) that can accurately represent the actual structure. However, mismatches between the FEM and the actual structure are inevitable due to modeling errors, real-world uncertainties, and operational conditions. Consequently, the damage diagnosis model trained on the FEM cannot be tested on the actual structure, given the discrepancy in training and testing data distributions. To address this, unsupervised domain adaptation, a subset of transfer learning, transfers knowledge from a source domain (i.e., FEM) to a related target domain (i.e., actual structure). Existing domain adaptation methods demand a large amount of unlabeled data from the target structure under both healthy and damaged states to train the damage diagnosis model, which is impractical. Physics-informed neural network (PINN) integrates physical laws governing a given dataset, reducing the number of training samples needed from the target domain. In this work, domain adaptation with adversarial training is employed to ensure that the extracted features from source and target domains maintain a similar data distribution. Moreover, PINN is incorporated into domain adaptation (i.e., physics-informed domain adaptation, PIDA) by constraining the network to learn the modal information of the structure, which helps alleviate the need for extensive training data and enhances damage detection performance. PIDA provides a novel and better solution for structural damage detection.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE TOPOLOGY AND SIZING OPTIMIZATION SOLVED WITH HIERARCHICAL-INSPIRED DEEP REINFORCEMENT LEARNING

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ABSTRACT

The discrete optimization of structures considering both discrete elements and discrete design variables can be formulated as a sequential decision process solved using deep reinforcement learning, shown in this work to efficiently provide adept solutions to a variety of problems. Beneficially, by modeling the optimization of discrete structures as a Markov decision process (MDP), the set of all feasible design solutions can be precisely represented and the MDP naturally, but not exclusively, accommodates discrete actions. In the context of discrete structural optimization, the states of the MDP correspond to specific structural designs represented as finite graphs, the actions correspond to specific topological and parametric design grammars which alter and transition the design to a new state and graph configuration, and the rewards are related to the improvement in the altered graph configuration's performance with respect to the design objective as well as the specified constraints. The consideration of both topological and parametric grammars enable the design agent to alter a given structural configuration’s element connectivity and assigned element parameters, respectively. However, in considering topological and parametric actions, both the dimensionality of the state and action space and the diversity of the action types available to the agent in a given state becomes significantly large, making the MDP learning task challenging. This work addresses optimization problems with large and diverse state and action spaces by significantly extending the deep reinforcement learning (DRL) approach implemented in prior work [1]. Specifically, a deep neural network architecture, adapted from hierarchical-inspired deep reinforcement learning (HDRL), is developed to better equip the agent in learning the type of action, including topological or parametric design grammars to apply, reducing the complexity of possible action choices available to the agent in a given state. This MDP-HDRL framework is applied to the discrete optimization of planar trusses considering both discrete elements and multiple discrete cross-sectional areas with the objective of minimizing displacement at a given node for a given external force(s), subject to volume and stability constraints. Through qualitative comparison with other considered alternative methods, the framework is observed to adeptly learn policies that synthesize high performing design solutions with respect to the design problem's specified objective and constraints.

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Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ADVANCING REGIONAL LANDSLIDE RISK ASSESSMENT BASED ON HYBRID DATA-DRIVEN AND PHYSICS-BASED SUSCEPTIBILITY MAPPING MODEL: A PIXEL-TO-SLOPE TRANSFORMATION

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ABSTRACT

Existing regional landslide risk assessments are mainly based on the pixel unit (also referred to as grid or cell units), which often results in significant disparities in risk levels within the same slope unit. This makes it challenging for engineers to accurately delineate high-risk areas. Addressing this issue, this study makes several contributions: (1) To date, very few studies have attempted to complement the advantages of data-driven and physics-based models for susceptibility mapping. We propose a pixel-based hybrid susceptibility mapping model, integrating infinite slope stability analysis and logistic regression using the optimal explanatory factors (elevation, land-cover type, safety factor). (2) A pixel-to-slope transformation method is introduced. Slope units are extracted through hydrological analysis, and the mean and maximum values of pixel susceptibility within each slope unit are calculated and analyzed. These two statistical parameters are then used to characterize the susceptibility of the slope units. The differences in susceptibility mapping results when using the mean value versus the maximum value for the transformation are compared. (3) A loss in accuracy occurs after transformation. To address this issue, a calibration method based on the standard deviation of susceptibility is proposed. It is recommended to conduct field verification when the standard deviation within a slope unit exceeds a certain threshold. The threshold depends on the available human and material resources in the specific area. (4) Population vulnerability and economic vulnerability are quantitatively analyzed, and a comprehensive vulnerability assessment matrix is proposed. A risk assessment matrix based on susceptibility and vulnerability is then constructed. Typical landslide-prone regions in the Three Gorges Reservoir, China, are used as the study area. The results show that the pixel-to-slope transformation of susceptibility mapping results significantly enhances their practicality in engineering applications, though some loss in accuracy occurs during the transformation. This accuracy loss can be effectively mitigated through the proposed calibration method. As the area covered by field verification increases, the area under the curve (AUC) value gradually improves. For example, by setting a threshold for the standard deviation of susceptibility at 0.3, conducting field verification across approximately 11.96% of the total area of Wushan County could increase the AUC value from 0.779 to 0.878. This study provides an easy-to-implement and effective method for regional landslide risk assessment.

Mechanics and modeling of pavement structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEVELOPMENT OF PLASTICITY-BASED FATIGUE MODEL IN ASPHALT BINDER

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ABSTRACT

Fatigue is one of major distresses in flexible pavement. Asphalt binder is the essential constituent in an asphalt mixture. Numerous studies have strived to develop models to predict fatigue behavior of asphalt binder, such as dissipated energy and viscoelastoplastic continuum damage model. However, improvement is still needed to develop robust fatigue model. This study aimed to develop the plasticity-based fatigue model for asphalt binder. This approach integrates creep tests with cyclic tests by regulating the load ratio (R), enabling precise control over the oscillation amplitude (A) and steady shear stress (S) of the applied load. Eyring's activated flow theory and the Sigmoidal model are utilized to characterize the plastic flow behaviors of asphalt within the examined temperatures and stress range. An effective fatigue prediction model is proposed to estimate asphalt materials' cycles to failure. The research findings demonstrate that Eyring's activated flow theory properly elucidates the intricate plastic flow kinetics observed in asphalt creep tests. The model developed in this study provides reasonable predictions that align with the cycles/time to failure measured in tests under various loading paths (R=0.1, 0.3 ,0.5, 0.7, 1) and temperatures.

Machine learning applications in wind engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXTRAPOLATING WIND-INDUCED PRESSURES ON ROOF SOFFITS OF LOW-RISE BUILDINGS USING FEW-SHOT LEARNING

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ABSTRACT

Current wind standards assume identical external wind pressure coefficients on roof soffits and adjacent wall surfaces. However, recent experiments suggest that this correlation significantly decreases with an increase in overhang width. This research introduces a few-shot learning model addressing the need for a machine learning approach that can more accurately and efficiently obtain the wind pressure coefficients on roof soffits when the overhang width is large (i.e., larger than 2 ft). A few-shot learning model is proposed to extrapolate the wind-induced pressures on roof soffits for low-rise buildings based on the wind tunnel dataset investigating three large overhang widths (2.4, 4.8, and 7.2 inches in 1:10 scale models) conducted at the Wall of Wind (WOW) Experimental Facility. Prior knowledge relating to zonal information and wind directions shown in the standard of minimum design loads and associated criteria for buildings and other structures (ASCE 7) is incorporated into the model. The proposed few-shot learning model was trained on scale model buildings with overhang widths of 2.4 and 4.8 inches and tested on a 7.2-inch overhang width case. A special set, named the ‘shot set’, is used in the proposed algorithm which only contains 5% of the 7.2-inch overhang width data samples, and the remaining 95% forms the testing set. The proposed meta-learning algorithm is trained on the training set to obtain good initial model parameters. With only a few gradient descent updates based on the data from the small ‘shot set’, the trained model can achieve good prediction performance for the test set data. When predicting the minimum wind pressure coefficient for both the southside and eastside soffit surfaces, low mean-squared errors (0.135 for the Southside and 0.152 for the Eastside) and high coefficient of determination values (0.783 for the Southside and 0.794 for the Eastside) were observed. This study marks the first application of few-shot learning techniques to extrapolate wind pressures across different roof overhang widths and provide reliable predictions that outperform the weak correlation between the soffit and the adjacent wall surface assumed currently. This model reduces reliance on physical wind tunnel experiments and requires only a low-resolution measurement tap configuration.

ROBUST VISION-BASED SUB-PIXEL LEVEL DISPLACEMENT MEASUREMENT USING A COARSE-TO-FINE STRATEGY

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ABSTRACT

Structural displacement has been a crucial proxy for the performance and health of a wide variety of civil infrastructure. Traditional displacement measurement approaches are costly, labor-intensive, and are primarily restricted to a few discrete points. Over the last decade, computer vision-based measurement approaches have been proposed to overcome these limitations, achieving non-contact and dense displacement measurement. In particular, phase-based optical flow (PBOF) has the capability of providing accurate and robust drift-free structural motion. However, conventional PBOF is restricted to estimation of small displacements. Herein, a coarse-to-fine strategy is proposed to extend the PBOF method to large-scale displacement measurement. First, the video is pre-processed to remove possible lens distortion, image noise and to select the target for measurement. Subsequently, the pixel location of the target in the current video frame is determined using weighted normalized cross-correlation matching (WNCC); reduction of the computation burden of this step is also considered. Finally, the displacement correction term is computed using the proposed improved PBOF algorithm, which is invariant to uniform illumination changes and can avoid potential phase wrapping issue. The refined displacement with sub-pixel level accuracy is obtained by combining the coarse displacement with the correction term. The efficacy of the proposed approach was validated with a base-excited 3-story building model in the laboratory. The results demonstrated that the proposed method achieves drift-free large displacement measurement with high efficiency, accuracy, and robustness.

Innovations and advances in passive, active, and semi-active structural control
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATION OF A VARIABLE LEAD ROTATIONAL INERTIA MECHANISM

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ABSTRACT

The increasing interest in nonlinear rotational inertia mechanisms (RIMs) stems from their diverse applications in energy storage and vibration control. Unlike a linear RIM, the effective mass produced by a nonlinear RIM can continuously vary during the response of the structure it is attached to. Most of the current research focuses on a specific type of nonlinear RIM that produces variable mass effects via a flywheel with masses incorporated into it that shift position based on the rotational velocity of the flywheel. While other types of nonlinear RIMs may have performance or practicality benefits, research into alternative forms of nonlinear RIMs is rare. This study addresses this gap by investigating the dynamic behavior and vibration control of a variable lead RIM. This RIM utilizes a ball screw mechanism to convert translational motion into the rotational motion of a flywheel, but the lead changes along the length of the shaft of the ball screw. The result of this configuration is that the effective mass provided by the device is a function of the relative displacement between the device's attachment points. The mechanism and dynamic model of the variable lead RIM is presented. A physical realization of a variable lead RIM attached to a single-degree-of-freedom mass-spring-damper system using a variable lead ball screw was produced as a part of this study. The natural frequency and response measures were evaluated from experimentally produced frequency response functions. The results of this study highlight the ability of variable lead RIM to shift the natural frequencies of the structure it is attached to and reduce the response of a system subjected to external excitation. The results of this work will encourage the further study of these innovative devices.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INELASTIC PROCESSES IN MATERIAL EVOLUTION WITH APPLICATION TO FRONTAL POLYMERIZATION

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ABSTRACT

We present a new thermodynamically consistent model for material evolution with application in frontal polymerization. The material evolution is modeled via the dependence of material parameters on an internal variable that represent the degree of cure. The model is motivated by experimental studies that characterize the evolution of material properties where the material is assumed to be elastic with continuously evolving material parameters. When evolving material parameters for materials that stiffen with time are employed in standard constitutive equations, it not only leads to violation of the second law of thermodynamics, but also result in non-physical behavior. To satisfy the thermodynamics constraints, an inleastic process that corresponds to the energy consumed in the evolution of the material needs to takes place concurrently. The inelastic process is formulated through multiplicative decomposition of the deformation gradient by introducing an internal variable representing inelastic strain. Finally, the flow rule for the inelastic strain is derived to enforce non-negative entropy production and to eliminate the non-physical behavior in the model.

The flow rule is applied alongside a thermo-chemo-mechanical model for frontal polymerization. The model considers factors, namely, heat generation, heat transfer, and reaction kinetics that incorporates the rate at which the monomers are converted into polymers with associated heat release. The balance of momentum and balance of energy equations are solved using stabilized finite element method that is consistently derived via Variational Multiscale Method (VMS). An algorithm that simulates the path of the printing process is employed in the printing simulation and several interesting test cases are presented.

KIRIGAMI STRAIN-RATE EFFECTS

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ABSTRACT

Kirigami, an ancient art form originating from the delicate craft of paper cutting, has emerged as an inspiration for modern engineering pursuits. Its principles, transforming 2D sheets into complex 3D structures, have ignited an era of innovation across multidisciplinary domains, encompassing deployable structures, advanced medical devices, and stretchable electronics.

A captivating facet lies in kirigami's potential to craft robust systems engineered to absorb and dissipate energy during highly dynamic events, such as blasts or impacts. When constructed from metallic materials exhibiting elastic-plastic behaviour, kirigami structures present a promising bedrock for pioneering concepts in energy dissipation systems.

Our exploration focuses on deciphering how varying strain rates impact the mechanical behaviour of kirigami structures. Employing reduced-order analytical models alongside finite element analysis, our investigation reveals the evolution in the behaviour of a simple parallel-cut kirigami configuration under increasing strain rates.

This evolution manifests as a shift from uniform to sequential deformation, akin to the behaviour observed in cellular structures under dynamic loads. Our comprehensive study explores the intricate relationship between cut pattern and strain-rate sensitivity, unravelling their influence on critical factors like dissipated energy and transmitted reaction forces. Moreover, we delve into how the cut pattern governs the structure's deformation mode and influences its failure mechanism.

Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RESIDENTIAL EXTERIOR WALL ASSEMBLY – RESPONSE TO EXPOSURE FROM ADJACENT POST-FLASHOVER COMPARTMENT FIRE

Daniel Gorham[1], Joseph Willi[1] and Gavin Horn[1]*

[1]UL Fire Safety Research Institute

ABSTRACT

Fire spread between buildings can overwhelm firefighting resources and can result in catastrophic wildland-urban disasters and conflagration events. When a building or structure ignites and burns it becomes a source of thermal exposure (radiant heat and direct flame contact) to adjacent targets, including neighboring buildings. Exterior walls comprise a large portion of typical residential structure's surface area and interfaces with several other building components (doors, windows, eaves, vents). If the exterior wall ignites fire penetrate through the assembly and/or spread (vertically and/or laterally) to impact other building components and subsequently enter the structure. In this study experiments were conducted to examined three residential exterior wall assemblies installed on a 4.9 m wide by 4.3 m high target façade: T1-11 plywood over oriented strand board (OSB) sheathing; Exterior Insultation and Finish System (EIFS) over exterior gypsum sheathing; and concrete fiberboard over OSB sheathing. The source exposure was a 3.7 m wide by 2.4 m deep by 2.4 m high compartment fire with a 2.4 m wide by 2.4 m high opening that was allowed to flashover. Separation distances between the source compartment and target façade ranged from 1.8 to 4 meters. Temperature and heat flux at the surface of the target façade were measured and response-to-fire of the wall assemblies was evaluated.

Understanding and managing the wildfire problem
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WINDOW FAILURE DURING EXTERIOR FIRE EXPOSURE

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ABSTRACT

Windows can be a vulnerability of structures exposed to exterior fires, like in the case of wildland-urban interface (WUI) fires. Numerous WUI fire case studies have identified the impact of radiative heat transfer to windows on structure loss. When windows fail, they provide a pathway for embers and/or flames to enter the structure and ignite interior contents.

Research conducted by UL's Fire Safety Research Institute has provided additional insight into window failure during fire exposure. Experiments were performed to study the reaction of different types of dual-pane windows when exposed to a post-flashover compartment fire. Double pane window assemblies with both panes plain (annealed) glass, both panes tempered glass, and one pane plain glass, one pane tempered glass were examined.

For each experiment, eight windows were mounted in a target facade placed across from a source compartment with an attached facade to simulate the exposure of a structure fire to a neighboring structure. The fire was ignited in the source compartment. After reaching flashover, the fire continued to vent out the front opening, exposing the target facade to the spill plume generated by the post-flashover fire. The duration of post-flashover exposures ranged from approximately four to ten minutes. Incident heat flux at the target facade and the heat flux transmitted through the window pane assemblies were measured during each experiment.

In general, plain (annealed) glass panes failed notably earlier than tempered glass panes. For windows with one pane plain glass and one pane tempered glass, the orientation of the panes impacted the performance of the window assembly. The average percent heat flux transmitted through the pane assemblies was similar across the different window types. Heat fluxes measured behind window pane assemblies exceeded critical values for autoignition of common household materials, even before any pane failure occurred in many cases.

This presentation will begin with a brief overview of the WUI fire problem and the role of structure-to-structure fire spread during WUI fire events. The impact of windows on fire spread and the extent to which WUI building codes address windows will be highlighted. Then, the experiments conducted for this research will be introduced. Key experimental results and takeaways will be discussed with an emphasis on improving WUI building codes and structure hardening guidance for homeowners in areas prone to WUI fire hazards.

Meshfree, peridynamic, and particle methods: Advancements and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ASSESSMENT OF THE APPLICABILITY OF MODERN RKPM METHODS TOWARDS A CONCRETE SIMULATION UNDER EXTREME EVENTS

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ABSTRACT

Due to its widespread usage in a variety of vital structural applications and infrastructure, the safety and performance of concrete under extreme events, such as impact or blast, is essential to understand and be able to calculate predictively. Towards this end, a number of constitutive models have been developed which seek to capture the wide range of behaviors present in concrete such as those related to hardening, softening, rate effects, fracture, etc. However, these material models only comprise a portion a of a given physics-based numerical analysis as they generally represent a discrete material point in a larger numerical framework. As a consequence, capturing large scale discontinuous phenomenology of concrete response such as fracture, fragmentation, scabbing, and spall are often dependent on the numerical framework the material model is embedded in.

In this work, the advantage of utilizing meshfree methods to provide this robust numerical framework for treating concrete under extreme events will be demonstrated using problems which demonstrate a wide range of concrete phenomenology. A series of concrete benchmark problems will be compiled which seek to show several types of phenomenology found within problems involving concrete materials. A modern RKPM [1] numerical code, KC-FEMFRE, will be applied to each of these benchmarks and the results and efficiency from running these benchmarks will be documented compared against previous results taken from open literature, widely-used commercial solid mechanics codes, and experimental results, when applicable. To ensure fair comparison between existing solvers, the K&C Concrete model [2] will be leveraged as a VUMAT in all simulation codes utilized in this study. This will alleviate any differences that might be constitutive model implementation specific and demonstrate applicability of meshfree for this problem domain against comparable options.

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Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING AND COMPARING 3D IMAGING TECHNIQUES FOR INSPECTIONS OF STRUCTURE RETAINING WALLS

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ABSTRACT

This presentation will discuss ongoing research into the use of 3D imaging techniques in civil engineering that is seeking to improve the accuracy, completeness, and efficiency of retaining wall inspections. Traditional inspection methods for retaining walls rely on inspectors to make qualitative assessments of the structure that inform a numerical rating system [1]. 3D imaging accurately captures the entire structure, going beyond the qualitative assessments and collection of discrete points that current retaining wall inspections utilize [2]. The presentation will discuss the details and evaluation of different methods including Structure from Motion (SfM), LiDAR, and Structured Light Scanning (SLS) for the retaining wall inspection. The first experiment being discussed pertains to a laboratory study that sought to determine the accuracy of SfM recreations of a retaining wall structure when compared to an SLS baseline. Three different cameras of varying quality were used to create SfM models of the lab trial structure that were then compared to their SLS counterparts. Cameras with high quality images yielded higher accuracies and the ‘banana’ or ‘doming’ effects were identified as an issue for iterations of the study that measured a straight section of wall. This study also examined two different means of comparing 3D models in the context of routine retaining wall inspection. Expanding on the work from this initial study, a second study is being conducted that assesses the accuracy of SfM retaining wall models collected in the field through manual UAV flights. This second study seeks to determine how UAV based SfM can best be implemented when site conditions require manual flight. In the third study, the impact of loss in data quality for UAV based LiDAR scans will be explored and compared to terrestrial LiDAR scans and survey measurements.

This research is being conducted to help refine the application of 3D imaging techniques in the specific application of retaining wall inspections as part of a project for the CTDOT.

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Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BAYESIAN MODEL UPDATING USING INCOMPLETE EIGEN-INFORMATION AND SPARSE IDENTIFICATION

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ABSTRACT

In this study, a novel Bayesian model updating approach that incorporates structural properties and features extracted from monitoring data is proposed. Previous studies have highlighted the detrimental impacts of modeling discrepancies on subsequent analyses, such as system identification, structural health monitoring, structural control, etc. [1,2]. Taking this into consideration, the proposed approach aims to infuse the available physical information and measurements for configuring the structural model. The proposed approach consists of two folds. Firstly, incomplete noisy eigenpairs obtained from vibration tests are utilized to determine the optimal solution of the mass and stiffness matrix. Thereafter, sparse identification is implemented to develop the governing equation of the concerned dynamical system. Consequently, the modeling inaccuracy induced in the eigen-information is compensated by the sparse identification while the structured system matrices mitigate the instability of the sparse identification. Moreover, as the benefit of Bayesian inference, the uncertainties of all estimates and the modeling performance can be quantified in terms of probability density functions [3]. It provides useful information to interpret the reliability of the estimation and modeling outcomes. The proposed approach successfully integrates physical information and limited data for optimal structural modeling with quantified uncertainty. To demonstrate the performance of the proposed method, we present an illustrative example of a bridge structure under various modeling conditions.

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4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHASE-FIELD MODELING ELECTRO-CHEMO-MECHANICAL COUPLING FOR ADVANCED CIVIL ENGINEERING MATERIALS

Congjie Wei[1], In Kyu Jeon[1], Yuxiang Gan[1], Yong-Rak Kim[1] and Chenglin Wu[1]*

[1]Texas A&M University

ABSTRACT

Civil engineering materials have come a long way to satisfy our growing demands of buildings and infrastructure such as smart (i.e., sensing), resilient (i.e., physical resistance), sustainable and durable (i.e., tunable chemical reactivity and stability), as well as energy storage capable (i.e., heat and electricity). This requires an in-depth understanding of the often-involved electro-chemo-mechanical coupling phenomenon that occurs during the synthesis, process, and forming of these advanced materials for various functions. In this paper, we introduced an energy formulation that combines the electrical, chemical, and mechanical potentials, as well as ionic capacitance potential, to achieve realistic coupling between the electro-chemo-mechanical coupling. The novel phase-field damage functionals will be introduced to show convergence and coupling among multi-physical fields. Specific examples, including a corrosion-cracking and an ionic store-and-release process, are benchmarked in a 1D setting by comparing with semi-analytical solutions with the help of the Laurent series of complex functions. The 2D benchmark cases were also conducted to show the capability and performance of the proposed phase-field modeling framework. In addition, a data-driven reduce-order phase-field modeling approach is also presented with potential phase-switching using a machine-learning-based inversion approach. A case study on the corrosion-cracking problem is demonstrated using the proposed approach.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING THE RESILIENCE OF COASTAL BRIDGES: THE INFLUENCE OF BOX GIRDER GEOMETRY ON WAVE FORCES VIA SPH SIMULATIONS

Gaoyuan Wu[1] and Maria Garlock[1]*

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ABSTRACT

The potential increase of the intensity and frequency of natural disasters led by climate change indicates higher risks for coastal bridges: they may be lifted off the pier or otherwise fail during hurricane and tsunami strikes because of elevated water and wave forces. This project investigates various geometries of box girder bridges via smoothed particle hydrodynamics (SPH) modeling, evaluating effective geometric forms and vulnerability. Specifically, we investigate the influence of the angle difference between the web and the top flange, as well as the integration of parapets on wave forces, including the maximum uplift force and the maximum horizontal force. Different wave characteristics and bridge elevations are considered. While both hurricane-induced and tsunami-induced waves would cause damage to coastal box girder bridges, we limit the scope to tsunami-induced waves and thus, solitary waves are employed. The numerical scheme is first validated by existing data in literature and then implemented for a parametric study. It is shown that the angle difference between the web and the top flange plays a significant role in the magnitude of the wave forces, especially when the bridges are elevated and tall waves strike. Moreover, the integration of parapets leads to higher risks for coastal bridges. The results provide insights on effective box girder bridge forms for coastal hazard mitigation, facilitating future research on innovative design of coastal bridges.

Towards resilient coastlines: Advancements and new approaches
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LIFE-CYCLE COST ASSESSMENT FOR PERFORMANCE-BASED WIND DESIGN OF A TALL CONCRETE BUILDING EQUIPPED WITH DAMPING SYSTEMS

Teng Wu[1] and Baichuan Deng[1]*

[1]University at Buffalo

ABSTRACT

The performance-based wind design (PBWD) methodologies attract growing interest in recent years. Industries, in general, welcome this transition since the experience from performance-based earthquake engineering indicates the PBWD may not only improve building response under extreme wind excitations, but also increase structural economy by allowing for nonlinear response in deformation-controlled components. However, the fact that structural wind design is usually controlled by the comfort criteria poses great challenges of taking full advantage of nonlinear behaviors and hence yields low economic benefits. The installation of a damping system shows advantages to improving the structural comfort behavior in an economically efficient way. In this study, a tall concrete building developed under the guidance of PBWD is equipped with two damping systems, namely passive viscous dampers and semi-active controlled magnetorheological (MR) dampers. To evaluate the economic benefits of both damping systems, a comparison study has been made using the life-cycle cost considering the initial design, installation of damping systems, and maintenance under wind hazards.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PHYSICS-INFORMED FAILURE PREDICTION FRAMEWORK USING HYSTERETIC LOOPS OF RC COLUMNS

Ting-Yan Wu[1], Rih-Teng Wu[1], Ping-Hsiung Wang[2], Tzu-Kang Lin[3] and Kuo-Chun Chang[1]*

[1]*National Taiwan University*
[2]*National Taipei University of Technology*
[3]*National Yang Ming Chiao Tung University*

ABSTRACT

The hysteretic performance of reinforced concrete (RC) columns is of paramount importance in the seismic analysis of bridge systems, as it dictates the overall stability and load-bearing capacity, thereby ensuring resilience against seismic forces and upholding public safety. The cyclic loading test and numerical modeling are frequently employed for constructing the hysteretic behavior and accessing the damage of RC columns observed under cyclic loads. While cyclic loading tests can capture the structural response in experiments, they incur high costs and demand substantial time and labor resources. In contrast, numerical methods offer efficient modeling of complex systems but may introduce deviations from real-world scenarios, compromising the precision of simulation results. In this study, a physics-informed deep generative framework is proposed, which is composed of two components, i.e., hysteresis curves prediction and surface damage generation. A sequence-to-sequence (Seq2Seq) model is developed to bridge the gap between the hysteresis curves, which are simulated from the finite element models and monitored in the experiments, respectively. Additionally, the physical features are extracted to provide comprehensive information for the condition of the generative model, which is developed to forecast the surface damage patterns of the bridge columns. Trained with 5 hysteresis loops and 110 surface damage samples obtained from cyclic loading tests conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan, the proposed framework can reconstruct the 5 hysteresis loops with a mean squared error of 0.0026 KN and generate the surface damage images of Fréchet Inception Distance (FID) 45.99. By incorporating information from the hysteresis loops, the generative model can predict damage patterns throughout the entire cyclic tests, even those not present in the training dataset. Numerous experiments have confirmed that incorporating additional physical information improves the fidelity of synthetic surface damage patterns. The proposed framework allows bridge engineers to assess potential damages and evaluate the hysteretic performance of RC bridge columns during seismic design and retrofit.

Repair and assessment of deteriorating critical infrastructure
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EXPERIMENTAL DESIGN AND DEEP NEURAL NETWORKS FOR PREDICTING THE CONDITIONS OF STRUCTURALLY DEFICIENT BRIDGES

Olivia Smith[1], Weidong Wu[1], Joseph Owino[1], Yu Liang[1], Lan Gao[1] and Dalei Wu[1]*

[1]The University of Tennessee at Chattanooga

ABSTRACT

The structural condition of bridges is influenced by a myriad of factors, including type, materials, loads, and environmental conditions. Identifying the most significant factors among these is crucial for assessing durability and serviceability. Experimental design techniques play a pivotal role in discerning the relative importance of these factors. By employing these techniques, a reduced set of influential factors can be determined and utilized as inputs for deep neural networks.

The reduced model factors are then fed into deep neural networks to train a regression model for predicting the conditions of structurally deficient bridges. Given the vast dataset encompassing over 615,000 bridges nationwide, it is imperative to automatically retrieve relevant data to enhance the efficiency and accuracy of the predictive model.

To achieve this, data mining techniques are employed to identify and extract pertinent information from the extensive National Bridge Inventory (NBI) database. Our research focuses on contributing to the field of data analytics by refining and optimizing the use of the NBI database for predictive modeling in the context of bridge structural conditions. This approach not only enhances the understanding of the factors influencing bridge conditions but also contributes to the broader field of infrastructure management and maintenance.

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Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PERSONALIZED EMOTION RECOGNITION USING FOOTSTEP-INDUCED FLOOR VIBRATIONS

Yuyan Wu[1], Yiwen Dong[1], Sumer Vaid[1], Gabriella Harari[1] and Hae Young Noh[1]*

[1]Stanford University

ABSTRACT

Emotion recognition, the process of identifying human emotions, enables various applications, including mental health monitoring and emotion-based smart home devices. Previous sensing methods for emotion recognition, such as wearable sensors, cameras, and microphones, are limited by discomfort, visual obstacles, and privacy concerns. To this end, we propose a novel emotion recognition system using footstep-induced floor vibrations which provides a non-intrusive, convenient, and privacy-friendly method for emotion recognition that overcomes the limitations of other methods. The underlying principle of our method is that individuals' emotional states influence their gait patterns, which, in turn, impact the floor vibrations induced by their footsteps. We can infer individuals' emotional states by capturing and analyzing unique gait patterns associated with various emotional states, sensed through footstep-induced floor vibrations. The main research challenge is that this approach performed poorly when encountering individuals who were newly observed without any samples in the training set. The poor performance is mainly due to the differences among individuals’ gait patterns resulting from their diverse walking habits and body configurations.

To address this challenge, we develop a personalized emotion recognition model that recognizes gait differences among people by comparing the similarities between the newly observed person and each person in the training set. Specifically, we first pre-train an emotion recognition model based on the footstep-induced floor vibration data in the training set. Then, we calculate the gait similarity index between the newly observed person and each of the people in the training set based on the learned representations of the footstep-induced floor vibrations obtained from the pre-trained model. Subsequently, we update and adapt the personalized emotion recognition model by assigning higher weights to individuals in the training set who exhibit similar gait patterns to the newly observed person. To evaluate our system, we conducted a real-world walking experiment with 20 participants. Participants assessed their emotions using the Self-Assessment Manikin emotion survey, including rating scales for valence (pleasant vs unpleasant) and arousal (calm vs excited), with scores between 1 and 9. Our method achieves a Mean Absolute Error of 1.54 for valence score estimation and 1.54 for arousal score estimation. This result is comparable to the state-of-the-art gait-based emotion recognition approaches.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A PHYSICS AND DATA CO-DRIVEN SURROGATE MODELING METHOD FOR HIGH-DIMENSIONAL RARE EVENT SIMULATION

Jianhua Xian[1] and Ziqi Wang[1]*

[1]*University of California, Berkeley*

ABSTRACT

In this talk, I will present a physics and data co-driven surrogate modeling framework for efficient rare event simulation of mechanical and civil systems with high-dimensional input uncertainties. The framework embodies a fusion of interpretable low-fidelity physical models with data-driven error corrections. The overarching hypothesis is that a well-designed simplified physical model can extract salient features of the original high-fidelity model, while machine learning techniques can fill the remaining gaps between the surrogate and original models. The coupled physics-data-driven surrogate model is adaptively trained using active learning, aiming to maximize the correlation between the surrogate and original model responses in the critical parametric region for a rare event. Due to the strong correlation between the well-trained surrogate and original models, an importance sampling step is finally introduced to drive the probability estimations toward the theoretically guaranteed solutions. I will present numerical examples of static and dynamic problems with high-dimensional input uncertainties (up to 1,000 input random variables) to demonstrate the proposed framework.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MPM LAGRANGIAN-EULERIAN HYDROCODE FOR SIMULATING BURIED EXPLOSIONS IN TRANSVERSELY ISOTROPIC GEOMATERIALS

Mian Xiao[1] and Waiching Sun[1]*

[1]Columbia University

ABSTRACT

Shock waves in geological materials are characterized by a sudden release of rapidly expanding gas, liquid, and solid particles. In engineering applications, these shock waves can often be triggered by underground explosions and has a profound effect on post-explosion behavior controlling. In fact, underground explosions have often been used as an engineering solution for large-scale excavation, stimulating oil and gas recovery, creating cavities for underground waste storage, and even extinguishing gas field fires. As such, hydrocodes capable of simulating rapid and significant deformation under extreme conditions can be a valuable tool for ensuring the safety of explosions. The objective of this paper is to propose the use of material point method (MPM) equipped with appropriate equation of state (EOS) models as a hydrocode suitable to simulate underground explosions of transverse isotropic geomaterials. To capture the anisotropic effect of the common layered soil deposits, we introduce an anisotropic version of the Mie-Gruneisen equation of state is coupled with a frictional Drucker-Prager plasticity model to replicate the high-strain-rate constitutive responses of soil. One advantage that MPM has against many other hydrocodes is the convenience for representing geometry, as those hydrocodes formulated in Eulerian grids have difficulty tracking the deformed material configuration without a level set. By leveraging the Lagrangian nature of material points to capture the historical dependence and the Eulerian calculation of internal force, the resultant model is capable of simulating the rapid evolution of geometry of the soil as well as the high-strain-rate soil mechanics of anisotropic materials. Three numerical examples are presented to verify and demonstrate the shock wave propagation and post-explosion behaviors for both isotropic and anisotropic geomaterials.

Computational geomechanics

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MPM LAGRANGIAN-EULERIAN HYDROCODE FOR SIMULATING BURIED EXPLOSIONS IN TRANSVERSELY ISOTROPIC GEOMATERIALS

Mian Xiao[1] and WaiChing Sun[2]*

[1]Columbia Universirty
[2]Columbia University

ABSTRACT

Shock waves in geological materials are characterized by a sudden release of rapidly expanding gas, liquid, and solid particles. In engineering applications, these shock waves can often be triggered by underground explosions and has a profound effect on post-explosion behavior controlling. In fact, underground explosions have often been used as an engineering solution for large-scale excavation, stimulating oil and gas recovery, creating cavities for underground waste storage, and even extinguishing gas field fires. As such, hydrocodes capable of simulating rapid and significant deformation under extreme conditions can be a valuable tool for ensuring the safety of explosions. The objective of this paper is to propose the use of material point method (MPM) equipped with appropriate equation of state (EOS) models as a hydrocode suitable to simulate underground explosions of transverse isotropic geomaterials. To capture the anisotropic effect of the common layered soil deposits, we introduce an anisotropic version of the Mie-Gruneisen equation of state is coupled with a frictional Drucker-Prager plasticity model to replicate the high-strain-rate constitutive responses of soil. One advantage that MPM has against many other hydrocodes is the convenience for representing geometry, as those hydrocodes formulated in Eulerian grids have difficulty tracking the deformed material configuration without a level set. By leveraging the Lagrangian nature of material points to capture the historical dependence and the Eulerian calculation of internal force, the resultant model is capable of simulating the rapid evolution of geometry of the soil as well as the high-strain-rate soil mechanics of anisotropic materials. Three numerical examples are presented to verify and demonstrate the shock wave propagation and post-explosion behaviors for both isotropic and anisotropic geomaterials.

Objective resilience: Harnessing emerging technologies for enhancing infrastructure and community resilience
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INTELLIGENT AGRICULTURAL MANAGEMENT SUBJECT TO CLIMATE VARIABILITY

Shaoping Xiao[1] and Zhaoan Wang[1]*

[1]*The University of Iowa*

ABSTRACT

According to a 2022 report from the United States Department of Agriculture (USDA), total farm production nearly tripled from 1948 to 2017. However, despite the growth, there remains a global food shortage. On the other hand, agricultural management, with a particular focus on fertilization strategies, holds a central role in shaping crop yield, economic profitability, and environmental sustainability. While conventional guidelines offer valuable insights, their efficacy diminishes when confronted with extreme weather conditions, such as heatwaves and droughts. Given these pressing issues, it becomes imperative to leverage new technologies to boost farm production, and one such solution is Precision Agriculture (PA). Precision agriculture, also known as ``precision farming" or ``prescription farming," utilizes information and technology-based agricultural management systems. These systems enable farmers to tailor their soil and crop management practices precisely to various weather/soil conditions on individual farmlands.

In this study, we introduce an innovative framework that integrates Deep Reinforcement Learning (DRL) with Recurrent Neural Networks (RNNs). Leveraging the Gym-DSSAT simulator, we train an intelligent agent to master optimal nitrogen fertilization management. Through a series of simulation experiments conducted on corn crops in Iowa, we compare Partially Observable Markov Decision Process (POMDP) models [1] with Markov Decision Process (MDP) models [2]. Our research underscores the advantages of utilizing sequential observations in developing more efficient nitrogen input policies. Additionally, we explore the impact of climate variability, particularly during extreme weather events, on agricultural outcomes and management. Our findings demonstrate the adaptability of fertilization policies to varying climate conditions. Notably, a fixed policy exhibits resilience in the face of minor climate fluctuations, leading to commendable corn yields, cost-effectiveness, and environmental conservation. However, our study illuminates the need for agent retraining to acquire new optimal policies under extreme weather events. This research charts a promising course toward adaptable fertilization strategies that can seamlessly align with dynamic climate scenarios, ultimately contributing to the optimization of crop management practices.

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Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

POTENTIAL DEVELOPMENT, MOLECULAR DYNAMICS, AND MULTISCALE MODELING OF TIB AND TI/TIB COMPOSITES

Shaoping Xiao[1], Siamak Attarian[2], Akram Ghaffarigharehbagh[1] and Yingbin Chen[1]*

[1]*The University of Iowa*
[2]*University of Wisconsin*

ABSTRACT

Boride ceramics, particularly titanium borides (TiB), are favored materials in extreme conditions due to their exceptional hardness and melting points. Titanium/titanium boride (Ti/TiB) composites exhibit promising potential for applications in aerospace, automotive, and biomedical industries. Despite their significance and the considerable effects invested in their fabrication and testing, limited modeling and simulations exist regarding the mechanics of these materials at various length scales, primarily due to the absence of reliable and accurate potential functions for Ti-B systems.

This study addresses the gap by employing diverse numerical methods to investigate the mechanics of TiB and Ti/TiB composites. Initially, density functional theory (DFT) is utilized to develop an interatomic potential for the Ti-B system, employing the second nearest-neighbor modified embedded atom method (2NN-MEAM) formulation. Subsequently, Molecular Dynamics (MD) simulations are conducted using the developed potential to explore the mechanics of TiB at the nanoscale, considering the effects of temperature and defects. Finally, peridynamics is employed to study the mechanical behaviors of Ti/TiB composites, particularly under high-speed impact.

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Modeling of materials with interfaces and scales using physics-based and machine-learning methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LINKING MICRO-MORPHOLOGY AND MACRO-MECHANICS: UNCERTAINTY QUANTIFIED PARAMETRICALLY UPSCALED CONSTITUTIVE MECHANICS MODEL (UQ-PUCDM) FOR COMPOSITES THROUGH PHYSICS-BASED MACHINE LEARNING

Yanrong Xiao[1], Deniz Ozturk[1], Xiaofan Zhang[1] and Somnath Ghosh[1]*

[1]Johns Hopkins University

ABSTRACT

This work develops an uncertainty qualified, parametrically upscaled constitutive mechanics model (UQ-PUCDM) for composites using Bayesian inference and machine learning methods. PUCDM, a microstructure-sensitive constitutive model, is thermodynamically consistent for multiscale analysis of unidirectional glass fiber-reinforced composites. This model uses explicit functions with Representative Aggregated Microstructural Parameters (RAMPs) that represent statistical distributions of fibers in the microstructure. With machine learning methods, the function forms of the PUCDM equations are determined to reflect the fundamental deformation characteristics of the aggregated response observed in the microstructural statistically equivalent RVEs' finite element model simulations. The UQ-PUCDM framework is built from computational homogenization of finite element simulations performed on a large set of microstructures and various load paths, followed by Bayesian inference from these results to derive probabilistic microstructure-dependent constitutive laws of the macroscopic material response. The framework derives probabilistic micro-structure dependent constitutive laws addressing multiple sources of uncertainty that accrue at the model development and response prediction stages, viz: (i) model reduction error, (ii) data sparsity, and (iii) microstructural variability of the material. A Taylor expansion-based uncertainty propagation method is developed to propagate uncertainties to the material response variables. Several numerical examples are provided to demonstrate UQ-PUCDM's accuracy. This study provides an insight into the physical constraints of applying the machine learning method to small mechanical data sets.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NANOSCALE CYLINDRICAL DEFECTS IN FLEXOELECTRIC SOLIDS

Jinchen Xie[1] and Christian Linder[1]*

[1]Stanford University

ABSTRACT

Flexoelectricity, characterized as a size-dependent phenomenon, enables strain gradients to induce electric polarization. This effect becomes notably pronounced near defects within flexoelectric solids, where significant strain gradients are typically observed. A comprehensive understanding of internal defects in flexoelectric devices and their associated multiphysics fields is imperative for elucidating their damage and failure mechanisms. Given the prevalence of circular-shaped cavities and inhomogeneities among various defect typologies, this study delves into an extensive investigation of plane strain problems associated with cylindrical cavities and inhomogeneities in flexoelectric solids [1, 2]. For the first time, we derive full-field analytical solutions for these problems, leveraging the principles of flexoelectricity, which encompasses pure strain gradient elasticity theory. Correspondingly, strain gradient elasticity solutions for plane strain problems involving cylindrical cavities and inhomogeneities are also established, marking a novel contribution to the field. Our findings demonstrate that the stiffness of inhomogeneities, the sizes of cylindrical defects, and the loading ratios in biaxial directions significantly influence the local electromechanical coupling behavior near these inhomogeneities. To compare with our analytical findings, we employ the mixed finite element method to approximate the solutions numerically. The congruence observed between the finite element outcomes and the analytical solutions underscores the reliability and rigor of this investigation. In summary, this research provides crucial insights into the behavior of defects in flexoelectric solids and lays a robust foundation for future studies on more complex defect typologies. It is a significant contribution to understanding flexoelectric materials and their applications in advanced technological domains.

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Smart IoT sensors and artificial intelligence for civil infrastructure monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DENOISING CALIBRATION AND PERFORMANCE EVALUATION OF LOW-FREQUENCY MEMS ACCELEROMETERS BASED ON GENERATIVE ADVERSARIAL NETWORK

Yanlong Xie[1], Jichuan Tang[2] and Weixin Ren[1]*

[1]Shenzhen University
[2]University of Notre Dame

ABSTRACT

MEMS (Micro Electro Mechanical System) accelerometer has gained considerable attention in recent years since it can be potentially used for smart sensing with edge computing in various fields. For large civil infrastructure, such as long-span bridges, and super-tall buildings, engineers are more interested in knowing the dynamic performance in a low-frequency range which is related to the comfort level and structural safety. In order to capture their modal characters, good performance of anti-noise sensors in a low-frequency band is required. However, noise interfering can not be eliminated from the MEMS sensors during the measurement. To address this issue, an adaptive denoising method for sensor calibration based on the generative adversarial network is proposed, including (i) signal pre-processing; (ii) data network training; and (iii) performance evaluation. Furthermore, a field measurement of the dynamic response of a long-span bridge is carried out with the comparison to conventional instruments. Results have shown the efficiency of the denoising method for civil applications.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFICIENT SAMPLE-BASED SENSITIVITY ANALYSIS FOR HIGH-DIMENSIONAL VARIABLES WITH NORMALIZING FLOWS

Ziluo Xiong[1] and Gaofeng Jia[1]*

[1]Colorado State University

ABSTRACT

Sobol' indices have been widely used in global sensitivity analysis to quantify the influence of the uncertainty of input variables on the variance of the system output. Among various approaches for evaluating Sobol' indices, the recently developed sample-based approach uses only one set of samples from an auxiliary probability density function (PDF) to evaluate the sensitivity to all input variables. However, a key step in the approach is to use kernel density estimation (KDE) to estimate the auxiliary PDF, which suffers from the curse of dimensionality and hinders its use for calculating sensitivity for groups of variables, which is of great interest for complex systems with many variables (or subsystems each represented by a subset or a group of variables). To address this challenge, this study extends the sample-based approach by introducing normalizing flows (NF) for efficient and accurate density estimation in place of KDE. NF are a family of methods for constructing complex distributions by transforming a simple PDF through a series of invertible mappings. It is an emerging generative machine learning model that allows not only efficient simulation of samples from a target PDF but also a direct estimation of the corresponding PDF values. The basic idea of the sample-based approach is to construct a joint auxiliary PDF based on the system performance function and PDFs of all input random variables. The Sobol' indices of any random variables (scalar or vector) can then be calculated based on a marginal distribution (of the joint auxiliary PDF) that is estimated with NF from a single sample set from the joint auxiliary PDF. Also, a novel adaptive stochastic sampling technique is proposed to efficiently obtain samples from the joint auxiliary PDF by training NF with a customized loss function minimizing the discrepancy between the learned PDF and joint auxiliary PDF. As an illustration, the proposed approach is applied to two high-dimensional benchmark problems. The results show that the proposed approach can accurately and efficiently evaluate Sobol' indices for high-dimensional input variables of a complex system.

Objective resilience: Computational advancements for performance-based engineering and resilience assessment of communities

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING TRAFFIC RESILIENCE FOR EMERGENCY EVACUATION BY EFFICIENT NETWORK-WIDE SPEED LIMIT OPTIMIZATION UNDER UNCERTAINTY

Ziluo Xiong[1] and Gaofeng Jia[1]*

[1]*Colorado State University*

ABSTRACT

Pressing threats from natural hazards (e.g., hurricanes and floods) have made efficient traffic evacuation critical to ensuring the resilience of vulnerable communities. During emergency evacuation, traffic management policies are often made to enhance the performance of transportation networks. Among the different policies, developing appropriate network-wide speed limits has been recognized as a promising one. To accurately assess the network performance, various uncertainties need to be considered, making the speed limit design computationally challenging because it corresponds to a high-dimensional optimization problem under uncertainty. In this regard, this study develops a new method to reliably and efficiently improve traffic resilience for emergency evacuation. Specifically, a transportation network performance modeling framework is first proposed to incorporate traffic efficiency and traffic safety concerns that are seldomly addressed simultaneously yet necessary in evacuation planning. Moreover, a novel optimization strategy is developed by artificially treating the network-wide speed limits as a high-dimensional random variable and formulating an augmented reliability problem to efficiently explore the uncertain network performance over the entire design space of speed limits. As a key step in the proposed approach, random samples need to be generated from a failure distribution. By leveraging an emerging generative machine learning model (i.e., normalizing flows), an adaptive stochastic sampling technique is designed to efficiently obtain a sufficient number of samples at low cost. Finally, an evolutionary algorithm is applied to derive an optimal speed limit design based on a surrogate of the network performance that is built upon the obtained samples from normalizing flows. The proposed method is applied to a real-world transportation network for demonstration. The results show that the proposed method can effectively resolve the network-wide speed limit design problem, facilitating prompt traffic resilience enhancement during emergency evacuation.

Probabilistic learning, stochastic optimization, and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN MODELING OF STOCHASTIC DIFFERENTIAL EQUATIONS

Yuan Chen[1] *and Dongbin Xiu**[1]

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ABSTRACT

We present a numerical framework for learning unknown stochastic dynamical systems using measurement data. Termed stochastic flow map learning (sFML), the new framework is an extension of flow map learning (FML) that was developed for learning deterministic dynamical systems. For learning stochastic systems, we define a stochastic flow map that is a superposition of two sub-flow maps: a deterministic sub-map and a stochastic sub-map. The stochastic training data are used to construct the deterministic sub-map first, followed by the stochastic sub-map. The deterministic sub-map takes the form of residual network (ResNet), similar to the work of FML for deterministic systems. For the stochastic sub-map, we employ a generative model, particularly generative adversarial networks (GANs) in this paper. The final constructed stochastic flow map then defines a stochastic evolution model that is a weak approximation, in term of distribution, of the unknown stochastic system. A comprehensive set of numerical examples are presented to demonstrate the flexibility and effectiveness of the proposed sFML method for various types of stochastic systems.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VIRTUAL FORCE FIELD AND COARSE-GRAINED MODELING FOR FAST SIMULATIONS ON CRUMPLING AND ASSEMBLING OF MASSIVE 2D MATERIALS BY DROPLET DRYING

Ziyu Chen[1] *and Baoxing Xu**[1]

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ABSTRACT

Two-dimensional (2D) materials, such as graphene, boron nitride and molybdenum disulfide, have attracted tremendous attention over the past few years for their exceptional electronic, mechanical and thermal properties underpinned by their extremely large specific surface area, often demonstrated at the single layer level. However, a bulk form of these 2D materials, either as powders or a monolith is necessary for most applications such as high-performance electrodes in energy storage, filters for waste water/gas treatments in environmental systems, and lightweight structures. Crumping of 2D materials by droplet evaporation creates a new form of aggregation-resistant ultrafine particles with more scalable properties such as high specific surface areas. Here, we will present a computational molecular framework to simulate the simultaneous process of crumpling and self-assembly of massive 2D graphene sheets and their competition by droplet drying. In the framework, a coarse-grained molecular dynamics model will be proposed to model graphene sheets and well calibrated by comparing with the full-scale atomistic model including stretching, bending and adhesive deformation. A virtual force field that exerts on the coarse-grained model of graphene through the well-defined decreasing rate of spherical radius will be developed to mimic the liquid evaporation-induced pressure and is confirmed with good agreement with full-scale simulation on solid-liquid interactions. Comprehensive simulations on graphene sheets in both fully suspended droplet and sessile droplet on a solid substrate will be performed to reveal the evolution of energy and morphology during crumpling and assembling, and the simulation results show remarkable agreement with theoretical predictions. More importantly, good agreement between simulations and theoretical predictions on both overall size and accessible area of assembled stable particle after complete evaporation of liquid will be obtained and compared with experiments. The proposed fast simulation modeling and approach could be extended to study a broad scope of other low-dimensional nanomaterials such as nanowires, nanotubes, nanofibers and nanoparticles, and will provide quantitative guidance for the low-cost manufacturing of their bulk quantities through aerosol-like, or printing process in which fundamental mechanism of large deformation, instability, and self-assembly by solution evaporation are expected.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ACTIVE AND PASSIVE FUNCTIONALITY OF PIEZOELECTRIC SENSORS FOR MONITORING HIGH-TEMPERATURE PIPING SYSTEMS IN LIQUID METAL REACTORS

Chenxi Xu[1], Talha Khan[1], Muhammad Khan[1], Matthew Daly[1], Alexander Heifetz[2], Derek Kultgen[2], Miguel A. Gonzalez Nunez[3], Ed Lowenhar[3] and Didem Ozevin[1]*

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ABSTRACT

Piezoelectric sensors can function as transmitters and receivers, making them suitable for passive and active structural health monitoring (SHM) methods. This study combines guided wave ultrasonics (GWU) and acoustic emission (AE) methods to monitor piping systems in advanced nuclear reactors. The AE method can pinpoint the location of defects in pipes in real time by using a linear array of sensors. GWU can classify the defect type and severity once its location is identified using the AE method. The liquid sodium piping network at the Mechanisms Engineering Test Loop (METL) facility at Argonne National Laboratory was instrumented with thirteen piezoelectric sensors strategically placed using waveguides to accommodate the high operational temperature. The sensitivity of the acoustic emission mode was demonstrated through pencil lead break simulations, which showed that the piping system operates as an excellent waveguide. In the guided wave mode, pulse signals were transmitted through each sensor. The experimental results were compared with numerical simulations. Furthermore, the numerical simulations were extended to study damage modes, such as creep and fatigue cracks near welds. Creep damage and fatigue crack were introduced as coalescence of pores and line crack near welds, respectively. The integration of guided wave ultrasonics and acoustic emission methods, coupled with the application of the same sensor network, proves to be a promising approach for SHM of piping systems in advanced nuclear reactors.

Advances in fluid-structure interaction
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NOVEL SUBMERGED BREAKWATER FOR PROTECTING COASTAL BRIDGES FROM EXTREME WAVES

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ABSTRACT

Extreme waves generated by hurricanes, together with storm surges, have led to severe damage and even failures in numerous offshore structures. In this study, an innovative submerged breakwater design, specifically engineered to bolster coastal infrastructure resilience against the devastating effects of extreme waves and storm surges, is presented. This new design, featuring three semicircular shells and a rectangular base, enables modular construction and rapid deployment, providing an alternative in coastal structures protection strategies. Utilizing a sophisticated high-fidelity numerical wave tank, the breakwater's efficacy is scrupulously assessed under an array of stringent conditions, encompassing variations in wave height, water depth, bridge submersion depth, and proximal spacing to the bridge.A second-order solitary wave model is utilized to simulate extreme wave conditions, providing a robust test of the breakwater's capabilities. The results demonstrate a considerable reduction in both horizontal and vertical wave forces on T-girder bridge decks when compared to traditional breakwaters made from the same materials, thus confirming the new design's superior efficacy.

Further examination focuses on three critical aspects of the breakwater's development. Detailed wavelet analysis sheds light on the significance of wave energy redistribution in the time-frequency domain in reducing transient impacting forces. Additionally, a validated ANSYS finite element model is utilized to investigate the dynamic responses of the breakwater under various wave conditions, highlighting the need for attention to tensile stress, particularly at the arch foot region. Nevertheless, the observed maximum tensile stress remains within the safety parameters for widely used construction materials such as C40 concrete, ensuring the design's practicality and safety. A predictive adaptive Kriging-based surrogate model, developed using advanced machine learning techniques, provides further insights into the optimal deployment of the breakwater. According to the model, positioning the breakwater in water depths less than 1.25 times its height can lead to a reduction in wave loads by more than 20%, offering a strategic advantage in coastal defense planning.

In conclusion, this study contributes a meticulously developed breakwater design to coastal infrastructure protection, combining extensive numerical analysis with pragmatic engineering considerations. The findings confirm the design's capacity to reduce the impact of extreme waves on coastal structures, thus offering a substantiated, effective solution to the challenges of coastal engineering.

Modeling and characterization of brittle and quasibrittle fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ASYMPTOTICALLY MATCHED EXTRAPOLATION OF FISHNET FAILURE PROBABILITY TO CONTINUUM SCALE

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ABSTRACT

Motivated by the extraordinary strength of nacre, which exceeds the strength of its fragile constituents by an order of magnitude, the fishnet statistics became in 2017 the only analytically solvable probabilistic model of structural strength other than the weakest-link and fiber-bundle models. These two models lead, respectively, to the Weibull and Gaussian (or normal) distributions at the large-size limit, which are hardly distinguishable in the central range of failure probability. But they differ enormously at the failure probability level of 10^(-6), considered as the maximum tolerable for engineering structures. Under the assumption that no more than three fishnet links fail prior to the peak load, the preceding studies led to exact solutions intermediate between Weibull and Gaussian distributions. Here massive Monte Carlo simulations are used to show that these exact solutions do not apply for fishnets with more than about 500 links.

The simulations show that, as the number of links becomes larger, the likelihood of having more than three failed links up to the peak load is no longer negligible and becomes large for fishnets with thousands of links. A differential equation is derived for the probability distribution of not-too-large fishnets, characterized by the size effect, the mean and the coefficient of variation.

Although the large-size asymptotic distribution is beyond the reach of the Monte Carlo simulations, it can be illuminated by approximating the large-scale fishnet as a continuum with a crack or a circular hole. For the former, instability is proven via complex variables, and for the latter via a known elasticity solution for a hole in a continuum under shear. The fact that rows or enclaves of link failures acting as cracks or holes can form in the large-scale continuum at many random locations necessarily leads to the Weibull distribution of the large fishnet, given that these cracks or holes become unstable as soon they reach a certain critical size. The Weibull modulus of this continuum is estimated to be about triple that of the central range of small fishnets. The new model is expected to allow spin-offs for printed materials with octet architecture maximizing the strength-weight ratio.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UPGRADE OF FRACTURE MECHANICS BY SPRESS-SPRAIN RELATIONS: LIMITING DAMAGE FIELD CURVATURE

Houlin Xu[1], Anh Nguyen[1], A. Abdullah Donmez[1] and Zdenek Bazant[1]*

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ABSTRACT

Realistic simulation of fracture propagation and, especially, fracture branching, is essential for meaningful assessment and prediction of the continued growth of hydraulic crack system in rock. It is expected that lateral branching of the hydraulic cracks may be stimulated by variation of salinity of injected water and its changes. To capture the lateral branching one must consider that the crack is actually a damage band with a front of finite width, governed by a triaxial tensorial damage law. This is evidenced by the recent discovery of the so-called gap test at Northwestern University. To simulate such fracture numerically, the classical crack band model must be adopted. A fresh improvement, called the smooth Lagrangian crack band model (slCBM), which uses the new concept of localization limiter based on displacement curvature limitation and the so-called “spress-sprain” relations, will be used. This improvement is able to resolve the damage variation across the crack band and the variation of crack band width capturing the dependence of fracture energy on the crack-parallel tectonic stresses. All this will be done in the context of inelastic poromechanics.

INSIGHTS INTO THERMOMECHANICAL PROPERTIES OF CROSSLINKED POLYMER NETWORK ASSISTED BY MACHINE LEARNING

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ABSTRACT

Crosslinked polymer network materials are distinguished by their complex mechanical and glass-forming properties, a result of their unique molecular characteristics. In this study, we delve into the intricacies of their structure-property relationship using machine learning (ML) techniques. Employing a dataset derived from coarse-grained modeling, we explored a range of sophisticated ML models, including Random Forest, Support Vector Regression (SVR), and Artificial Neural Networks (ANNs). The Random Forest model emerged as the standout performer, distinguished by its minimal Root Mean Square Error (RMSE). To further refine our approach, we implemented ensemble methods and advanced hyperparameter optimization techniques, such as grid search and Bayesian optimization. Our investigations revealed the profound impact of molecular factors, particularly cohesive energy and chain stiffness, on the mechanical attributes of these materials. We ensured the credibility of our ML models through stringent cross-validation and strategies to mitigate overfitting. The insights gained from this study highlight the transformative potential of ML in deciphering and influencing the complex behaviors of polymer networks, heralding a new era of customized material design.

Surrogate modeling for uncertainty quantification, optimization, and statistical inference in engineering applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ADAPTIVE SURROGATE-BASED MULTI-FIDELITY MONTE CARLO SCHEME FOR PROBABILISTIC ANALYSIS OF NONLINEAR SYSTEMS SUBJECT TO STOCHASTIC EXCITATION

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ABSTRACT

To investigate the performance of engineered systems under general stochastic excitation in the context of uncertainty propagation, a considerable number of high-fidelity nonlinear analyses are generally required when implementing many state-of-the-art probabilistic frameworks, which can become computationally infeasible for complex systems. To minimize the computational cost while preserving accuracy, an adaptive surrogate-based multi-fidelity Monte Carlo (MFMC) scheme is presented for efficiently propagating uncertainties and predicting inelastic responses, and therefore, estimating probabilities of failure. In this approach, all available high-fidelity numerical simulations are concurrently employed as the training data for a surrogate model, based on a Gated Recurrent Unit (GRU) deep learning network, for predicting nonlinear dynamic responses which then serves, within the MFMC scheme, as a cost-effective low-fidelity model that correlates well with the high-fidelity model. To derive the quasi-optimal trade-off between the approximation quality of the low-fidelity model and the computational demand for training, an adaptive sampling scheme is introduced. This scheme seeks the minimum training data that ensures an adequate correlation between the high- and low-fidelity models with minimal variance, as determined through K-fold cross-validation. The proposed scheme is demonstrated to be capable of estimating failure probabilities for various limit states of interest through its application to a full-scale high-rise steel building under stochastic wind excitation. In addition to being significantly faster than state-of-the-art high-fidelity probabilistic frameworks, the scheme is remarkably accurate in reproducing the inelastic responses of structural models characterized by complex material behaviors, such as steel fatigue and initial imperfections.

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICAL ANALYSIS OF SEGMENTED TUNNEL STRUCTURES UNDER ACTIVE FAULT ACTIONS

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[2]CEA

ABSTRACT

To enhance the seismic resilience of transportation infrastructure systems, the idea of a segmented tunnel structure system has been proposed when tunnel engineering passes through active faults. It is believed that segmented tunnels have a better ability to adapt to seismic fault deformations, thereby reducing damage caused by faults and making it easier to restore traffic functions. However, the mechanical properties, failure principles, and applicable conditions of the disconnected segmental tunnel lining still need further study. This work takes a mountain tunnel project as an example, using finite element calculation methods to explore the mechanical properties of fully disconnected tunnel lining under fault action. The orthogonal experimental method was used to analyze the effects of factors such as the length of the lining segment, the width of the fault fracture zone, and the dip angle of the fault on the damage status of the lining at different levels of fault action. Results show that the use of segmented design is an effective measure to adapt to the action of faults. By utilizing the rigid motion between segments, the concentrated displacement of faults can be dispersed, reducing the forced displacement level acting on segmented tunnels and significantly reducing the degree of damage. The factors that affect the range of tunnel damage are found to be: fracture width, lining segment length, and fault dip angle. However, there are significant differences in the performance of tunnel segment lining under different fault action conditions, which have not been mentioned in previous studies. Therefore, a reasonable segment plan should be selected based on the type of active fault. In addition, the ability of segmented tunnels to adapt to fault activity is closely related to the performance of the selected materials. This study further compared and analyzed the stress performance of high-strength concrete and ultra-high strength concrete lining segments under the same fault action conditions. It is believed that materials with higher strength and yield point should be selected as lining materials for segment design.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF LIQUID CRYSTAL ELASTOMER MATERIALS WITH A NONUNIFORM DIRECTOR FIELD

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ABSTRACT

Nematic Liquid Crystal Elastomers (LCEs), containing rod-shaped mesogen moieties, are gaining significant attention for their ability to create multi-stimuli responsive actuators, morphing structures, and color-changing materials. The reorientation of these mesogens in response to external stimuli, coupled with network deformation, engenders unique viscoelastic behaviors and enhanced energy dissipation capacity. In this study, we introduce a robust topology optimization framework designed to facilitate the fabrication of monodomain LCE structures with an initially nonuniform director field. By leveraging this framework, it becomes possible to tailor the mechanical and optical properties of the LCEs to specific application needs. In this research, we design our method to simultaneously optimize both structural topology and director patterns in LCE structures. To achieve this, we integrate our algorithm as a User-defined element within the ABAQUS finite element suite to accelerate the processing speed of nonlinear finite element simulations. Furthermore, this study utilizes a time-dependent adjoint method, ensuring numerically precise and efficient design sensitivity analysis. Several numerical examples, focusing on compliance minimization and energy dissipation maximization, are presented to demonstrate the advantages of optimizing both the topology and the initial director field in our designs. These examples underline the effectiveness of topology optimization in fully exploiting the capabilities of initial director patterns. We anticipate that this topology optimization framework will be instrumental in advancing design processes in a broad array of applications, ranging from soft robotics and programmable metamaterials to sophisticated energy absorption systems.

Data-driven approaches to engineering mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A NEURAL OPERATOR LEARNING APPROACH TO MODEL POROELASTODYNAMICS OF ROCKS

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ABSTRACT

Coupled physics processes involving fluid flow in porous media play a key role in various engineering and geophysical applications such as CO2 sequestration and energy mining from unconventional reservoirs. This work takes advantage of deep learning to capture the poroelastodynamics of rocks using elastic waveform and acoustic pore pressure measurements. The main challenges in this vein are three-fold, namely: (i) multi-physics nature of data, (ii) multi-scale poroelastic properties such as the Lame constants, permeability coefficient, Biot modulus and effective stress coefficient, and (iii) asymmetric datasets where the measurements are dense in terms of elastic displacement but sparse when it comes to pore pressure. To help address these issues, kernel learning by way of the Fourier neural operators (FNO) [1,2] is employed to model the dynamical behavior of rocks in the frequency domain from partial and/or full waveform data in terms of elastic displacement and pore pressure. To this end, the rock is modeled as a poroelastodynamic operator that maps any external excitation to its associated displacement and pore pressure response such that the rock's constitutive behavior is naturally embedded as network parameters and learned from the data. Compared to classical architectures (defined by maps between finite-dimensional Euclidean spaces), the most notable advantages of FNOs are their resolution independence (thanks to mapping between infinite dimensional spaces) and their extrapolation capability to unseen scenarios (through parametrizing physical operators instead of solution instances). As a result, once the FNO is trained, solving for a new input only requires a forward pass of the network which integrates constitutive modeling, identification of poroelastic properties, and response prediction. By utilizing multi-frequency data as well as proper data and loss function scaling, we demonstrate that a robust and stable operator learning from poroelastic waveforms is achievable.

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EFFICIENT DNN MODELING OF UNKNOWN PDE SYSTEMS

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ABSTRACT

We will introduce a new framework called Flow Map Learning (FML), designed for the approximation and recovery of unknown time-dependent partial differential equations (PDEs) using solution data. This approach is different from traditional methods, which typically concentrate on identifying individual terms within PDEs. Instead, our focus is on numerically approximating the flow map: the mapping between the solutions at two different time instances, of these PDEs. We present a deep neural network (DNN) structure that closely matches the actual flow map of the PDE, which improves the accuracy of our model's estimates. This DNN-based FML extends to various scenarios, including linear and nonlinear scalar PDEs, systems of PDEs, and differential-integral equations, demonstrating versatility in both one and two dimensions.

Advances in geomechanics and geophysics for modern sub-surface technology and natural hazard
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SCALING EFFECTS IN REDUCED PHYSICAL TESTS: INSIGHTS FROM A GRADIENT-TYPE NONLOCAL PLASTICITY MODEL

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ABSTRACT

Mapping the measured performance of small-scale physical models to prototype scale involves grappling with scaling effects stemming from the interaction between the tested system and finite-dimensional plastic deformation zones. Although higher-order continuum models provide opportunities to quantify these effects, no study has assessed the influence of shear deformation zones on the performance of reduced-scale models. This study addresses this gap through gradient-type nonlocal plasticity. Specifically, a hardening-softening non-associative Mohr-Coulomb constitutive model is introduced and augmented with an over-nonlocal formulation. Within this framework, a closed-form expression for shear band thickness in full-field problems is derived. Analyses of Scaling effects are conducted in various systems, encompassing soil specimens under plane strain compression, reduced-scale shallow foundations, and pullout plate anchors. The simulations, in alignment with experimental data, reveal that as the size of the geo-system decreases, the load-displacement responses display heightened load-bearing capacity and more pronounced strength loss with further deformation. Furthermore, it is observed that the spatial extent of the plastic zone is contingent upon the size of the system relative to the intrinsic material length scale. The analyses also indicate that the mode of deformation undergoes a transition from strain localization to a diffuse plastic zone with a reduction in model size. These simulations not only offer valuable insights into the behavior of scaled geo-systems but also inspire the formulation of novel scale correction coefficients. This enhancement of model-to-prototype rescaling procedures, contingent on shear band thickness and system size, has the potential to improve the accuracy with which centrifuge test measurements can be used for engineering design.

Computational methods for stochastic engineering dynamics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STOCHASTIC SUBSPACE VIA PROBABILISTIC PRINCIPAL COMPONENT ANALYSIS FOR MODEL-FORM UNCERTAINTY

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ABSTRACT

This paper proposes a probabilistic model of orthonormal matrices based on the probabilistic principal component analysis (PCA). Given a sample of vectors in the embedding space, commonly known as a snapshot matrix, this method uses quantities derived from the PCA to construct distributions of the sample matrix as well as orthonormal matrices of all ranks. It is applicable to projection-based reduced-order modeling methods, such as proper orthogonal decomposition and related model reduction methods. Whereas existing methods use the tangent space of a matrix manifold to carry out probabilistic modeling of reduced-order basis, the proposed method carries out the probabilistic modeling of the subspace itself. This approach helps us find the probability distribution's analytical form in certain cases. The stochastic reduced order basis (SROB) thus constructed can be used, for example, to characterize model-form uncertainty in computational mechanics. The proposed method has multiple desirable properties: (1) it is naturally justified by a probabilistic interpretation of PCA and has analytic forms for the induced probabilistic models on related matrix manifolds; (2) it satisfies linear constraints, such as boundary conditions of all kinds, by default; (3) it has only one hyper-parameter, which greatly simplifies hyper-parameter training; (4) its algorithm is very easy to implement. We compare the proposed method with existing approaches visually in a low-dimensional example and demonstrate its performance in characterizing the uncertainty in a dynamics model of a space structure.

Civil infrastructure in a changing climate: From nonstationary risk assessment to developing adaptation strategies
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PROJECTION OF TROPICAL CYCLONE ACTIVITIES UNDER FUTURE CLIMATE

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ABSTRACT

To investigate the TC genesis under future climate, future TC events will be produced by using the global climate modeling (GCM) data. Eight global climate models of CMIP6, including GFDL (Geophysical Fluid Dynamics Laboratory Climate Model) climate models (e.g., CM4 and SPEAR), will be used. The following two combined climate change scenarios will be considered in this project, which are SSP5-8.5 and SSP3-6. First, the annual occurrence number will be generated based on the Genesis Index (GI) (Tippett et al., 2011; Scamargo et al., 2014). This index is based on the Poisson Regression of historical TC occurrence number and large-scale environment factors obtained from the GCM data. Second, the probability function of TC genesis location/time for future climate will be obtained by modifying the function under the current climate. To represent the future TC climatology, 10,000 simulation years of TC events will be produced using Monte Carlo Simulations by following the probability density distribution under future climate. Then, statistical analysis will be conducted to characterize the TC climatology under the given global climate, in terms of the spatial and temporal (seasonal and interannual) variability of the "observed" TCs under future climate.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-PHYSICS MODELING FOR METAL ADDITIVE MANUFACTURING: MELT POOL DYNAMICS, DEFECTS, AND POWDER SPATTERS

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ABSTRACT

Existing metal additive manufacturing (AM) models have difficulty handling the laser-metal interaction and associated boundary conditions (BCs) that significantly influence part quality metrics, such as defect and surface roughness. This talk presents a sharp-diffusive interface computational method for simulating multiphysics processes in metal AM, focusing on better handling the gas-metal interface, where metal AM physics mainly occurs. The framework consists of two components. The first is a mixed interface-capturing/interface tracking method to explicitly track the gas-metal interface topological changes without mesh motion or remeshing. The second is an enriched immersed boundary method (EIBM) to impose the critical flow, heat, and phase transition Neumann BCs, which are enforced in a smeared manner in current AM models, on the gas-metal inter-face with strong property discontinuity.

I will demonstrate how the developed model elucidates the fundamental metal AM physics (e.g., melt pool dynamics, keyhole instability, and powder spattering) and predicts critical part quality-related quantities (e.g., defect and surface roughness). The proposed framework’s accuracy is assessed by thoroughly comparing the simulated results against experimental measurements from NIST and Argonne National Laboratory using in-situ high-speed, high-energy x-ray imaging. I will also report other important quantities that experiments cannot measure to show the framework's predictive capability.

Mechanics and modeling of pavement structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VARIABILITY IN COMPACTION OF ASPHALT MIXTURES--EXPERIMENTAL INVESTIGATION AND PROBABILISTIC MODELING

Tianhao Yan[1], Jia-Liang Le[2], Mugurel Turos[2] and Mihai Marasteanu[2]*

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ABSTRACT

Compaction of asphalt mixtures is a crucial step in pavement construction. One primary concern related to compaction is its variability, which influences the uniformity of field density and, consequently, the overall quality of asphalt pavements. The present paper investigates the variability in asphalt mixture compaction through a combination of experiments and probabilistic modeling. In the experimental study, laboratory gyratory compaction is employed to characterize the compaction behavior of mixtures. The standard deviation of 12 replicates is calculated to evaluate the compaction variability for a particular mixture. Experiments are conducted on mixtures with different aggregate sizes and specimens of different heights to investigate the effects of aggregate and specimen sizes on compaction variability. The results show that larger specimen sizes decrease compaction variability, whereas larger aggregate sizes increase compaction variability. A mechanistic-based probabilistic model is developed for gyratory compaction to provide theoretical insights and explanations for the experimental observations. The model captures the inherent randomness of asphalt mixtures by simulating the spatial distribution of density as a Gaussian random field. The aggregate size is accounted for through the auto-correlation length of the random field. Variability in gyratory compaction process is modeled through Monte Carlo simulation. The simulated compaction process matches well the experimental results. Thus, the probabilistic model provides a theoretical explanation for the influences of specimen and aggregate sizes on compaction variability. This study enhanced our understanding of variability in the compaction of asphalt mixtures stemming from material heterogeneity and shed light on improving the reliability of asphalt pavement construction.

A PHYSICS-INFORMED PROBABILISTIC MACHINE LEARNING APPROACH FOR HIGH-COMPACTABILITY ASPHALT MIX DESIGN

Tianhao Yan[1], Yuxiang Wan[2], Mugurel Turos[2], Qizhi He[2], Jia-Liang Le[2] and Mihai Marasteanu[2]*

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ABSTRACT

Due to the physical complexity of asphalt mixtures, traditional asphalt mix design methods have relied heavily on empirical rules and trial-and-error, leading to a time-consuming design process and sub-optimal outcomes. To address these challenges, this paper introduces a physics-informed probabilistic machine learning framework that correlates material composition with the mechanical performance of asphalt mixtures. Our focus in this study is on applying this framework to optimize the compaction performance of asphalt mixtures. A physics-informed neural network (PINN) is employed, integrating the physical law for asphalt mixture compaction into the machine learning framework to enhance accuracy and rationality of predictions. A Bayesian Neural Network (BNN) is employed in combination with the PINN to quantify prediction uncertainties arising from the lack of data and inherent variability in the mechanical behavior of the material. The proposed machine learning model is trained and validated using material composition and laboratory gyratory compaction data obtained from a wide variety of previous mix designs. Results demonstrate the model's accuracy and its ability to capture prediction uncertainties, suggesting its potential application for designing and optimizing asphalt mixtures to improve compaction and field density. The proposed physics-informed probabilistic machine learning framework has promising potential to facilitate asphalt mix design practices.

BIM-BASED CONDITION ASSESSMENT AND BIM-FEM INTERCONNECTION FOR BRIDGES

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ABSTRACT

Infrastructure structures undergo a lengthy replacement cycle for components, which pose challenges in timely repairs and replacements. Therefore, it is crucial to establish a proper maintenance plan and develop efficient bridge history data based on the digitization of past and present maintenance information. The lack of integration in existing maintenance data hampers accurate condition assessments. To address these issues, ongoing attempts are being made to integrate and manage maintenance data based on Building Information Modeling (BIM). Efficient construction of maintenance data using BIM requires technology that allows visual confirmation of inspection data and the identification of damage location and size. In this study, an algorithm is proposed to extract damages from exterior damage images and generate a BIM mapped with these images, which enables automatic past and present condition assessments of a bridge including bridge components. Furthermore, to enhance interoperability between BIM and structural analysis, an algorithm is suggested to convert the BIM into finite element model with nodes and elements, incorporating material and sectional properties. The numerical analysis model, created based on the linked information, undergoes an analysis according to predefined damage scenarios. The results of the numerical analysis are then updated into the BIM. Subsequently, a condition rating assessment is conducted based on the updated damage information. This approach establishes a comprehensive history of bridge inspection and diagnosis data, which facilitate efficient maintenance and aids in the prevention of future damage.

Advances and applications of elasticity within applied mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE GENERAL EQUILIBRIUM OF ELASTIC LAYERED SYSTEMS (GELS), AN OPEN-SOURCE IMPLEMENTATION IN PYTHON

David Yang[1]*

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ABSTRACT

Hankel Transforms of the biharmonic operator on a potential function are used to solve for the stresses and displacements in an elastic body under an axisymmetric load using cylindrical coordinates. The potential function of a fourth order partial differential equation reduces to a transformed second order ordinary differential equation with repeated roots. Four constant coefficients are determined from the boundary conditions. Solving the multiple elastic layer problem requires finding the four constant coefficients for each layer at each value of the Hankel transform variable. This implementation follows the solution as documented in Crawford, Hopkins and Smith, Theoretical Relationships Between Moduli for Soil Layers Beneath Concrete Pavements.

The one-layer solution requires finding only two constant coefficients from the boundary conditions and can be solved analytically for a normal uniform, circular surface load. Substituting the two constant coefficients into the Inverse Hankel Transforms to get the stresses and displacements, solutions in integrals of Bessel functions of the first kind, order zero and one are found. The Laplace Transforms of those Bessel functions matches the solutions of Boussinesq and Egorov, as documented in Harr, Foundations of Theoretical Soil Mechanics.

This implementation will be used to plot the stresses and displacements of an elastic layered system with layer thickness as a variable and the subgrade modulus as a variable under a multiple wheeled vehicle. The origin of this implementation is from the University of Illinois, Urbana-Champaign, Multiple Wheel Elastic Layer Program (MWELP), from the early 1970s.

Multiscale behavior of damage and healing mechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A LOCALIZING GRADIENT DAMAGE MODEL FOR THE DYNAMIC FRACTURE OF QUASI-BRITTLE MATERIALS AND ITS SIMPLE IMPLEMENTATION IN ABAQUS

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ABSTRACT

This presentation focuses on the dynamic fracture of quasi-brittle materials such as concrete and ceramics under different loading rates. With a view towards an ease of implementation, a simple form of damage model is considered with the necessary constitutive relations, to adequately capture the dynamic fracture responses under mixed mode loading conditions. Specifically, an energetic split into tensile and compressive components enabled the imposition of damage descriptors only on the former, to avoid spurious compression induced damage in mixed mode dynamic fracture phenomenon. Moreover, a history-dependent dynamic increase factor is introduced to capture the rate dependent behavior accurately, without inducing numerical instabilities. The numerical solutions are regularized via the localizing gradient enhancement to give sharp damage profiles resembling the development of macroscopic cracks. Finally, to facilitate an ease of implementation in the commercial software ABAQUS, the class of built-in thermal-mechanical elements is utilized, together with the VUMAT-VUMATHT subroutines. Validation of the model's capabilities is demonstrated through the Compact Tension Test and the Kalthoff-Winkler Test, underscoring its potential to accurately model the rate-dependent effect in dynamic mixed mode fracture.

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Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPERATOR LEARNING FOR SOLVING PDE FORWARD AND INVERSE PROBLEMS

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ABSTRACT

Learning operators between infinitely dimensional spaces is an important learning task arising in wide applications in machine learning, data science, mathematical modeling and simulations, etc. This talk introduces a new discretization-invariant operator learning approach based on data-driven kernels for sparsity via deep learning. Compared to existing methods, our approach achieves attractive accuracy in solving forward and inverse problems, prediction problems, and signal processing problems with zero-shot generalization, i.e., networks trained with a fixed data structure can be applied to heterogeneous data structures without expensive re-training. Under mild conditions, quantitative generalization error will be provided to understand operator learning in the sense of non-parametric estimation.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

QUANTIFYING NON-UNIQUENESS IN MODEL UPDATING AND DAMAGE DETECTION FOLLOWING A BAYESIAN APPROACH

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ABSTRACT

Model updating aims at providing accurate models to capture actual dynamic behaviors of structures based on experimental data. The updated models can then be used for revealing possible structural damage information. Uncertainties always exist in model updating due to incomplete information, i.e., unknown measurement noise and modeling errors because of imperfect modeling assumptions. These uncertainties usually cause the problem of non-uniqueness or local identifiability, i.e., multiple equivalent models can fit the experimental data almost the same well. Locating all these equivalent models in a high-dimensional parameter space is a challenging task. Moreover, including all of them for representing the target structure needs a theoretical basis. This work employs a Bayesian probabilistic framework for model updating, so that the uncertainties can be quantified, and thus all the equivalent models can be considered naturally. An parameter space-search algorithm is proposed to systematically locate all the equivalent models. Damage detection for a problem with multiple equivalent models using the tranditional method is not possible because there will be multiple models for both the undamged and damaged structure, and the one-to-one correspondence for calculating stiffness reduction is not straightforward. A new probabilistic framework for damage detection for locally identifiable problems is proposed. A transmission tower under laboratory conditions with limited modal parameters was used to verified the proposed method.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SIMULTANEOUS PROPAGATION OF HYDRAULIC FRACTURES FROM MULTIPLE PERFORATION CLUSTERS IN LAYERED TIGHT RESERVOIRS: NON-PLANAR THREE-DIMENSIONAL MODELLING

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ABSTRACT

A hydromechanical coupled finite-discrete element method, which considers the non-planar three-dimensional growth, pressure continuity along the horizontal well, dynamic flow rate distributions among clusters, perforation friction, and fracturing fluid leakage, is employed to simulate the simultaneous growth of hydraulic fractures from an array of five perforation clusters in tight reservoirs interbedded with alternating stiff and soft layers. The simulation results highlight that the stress shadow induced by the non-planar propagation of the outmost hydraulic fractures stops the planar growth of the interior and middle hydraulic fractures and causes uneven fracturing fluid distribution among perforation clusters. The results demonstrate that the generated fracture pattern in the stage becomes more symmetric overall with the decreasing modulus of the soft layers. As the soft layer's modulus decreases, the total fracture height decreases significantly, but the local fracture aperture distribution increases, which leads to the reduction of total fracture area and leak-off volume of fracturing fluid as well as the increase of total fracture volume.It is also found that the adjustment of pumping rate is more effective than using nonuniform cluster spacing in promoting the simultaneous hydraulic-fracture growth in layered tight reservoirs.

Physics informed machine learning (PIML) for mechanics of porous media
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IN-CONTEXT OPERATOR LEARNING WITH DATA PROMPTS FOR DIFFERENTIAL EQUATION PROBLEMS

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ABSTRACT

We introduce the paradigm of “in-context operator learning” and the corresponding model “In-Context Operator Networks” to simultaneously learn operators from the prompted data and apply it to new questions during the inference stage, without any weight update. Existing methods are limited to using a neural network to approximate a specific equation solution or a specific operator, requiring retraining when switching to a new problem with different equations. By training a single neural network as an operator learner, rather than a solution/operator approximator, we can not only get rid of retraining (even fine-tuning) the neural network for new problems but also leverage the commonalities shared across operators so that only a few examples in the prompt are needed when learning a new operator. Our numerical results show the capability of a single neural network as a few-shot operator learner for a diversified type of differential equation problems, including forward and inverse problems of ordinary differential equations, partial differential equations, and mean-field control problems, and also show that it can generalize its learning capability to operators beyond the training distribution.

Reference: https://www.pnas.org/doi/10.1073/pnas.2310142120

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

HYDRATION MECHANISM OF CEMENT PASTES WITH THE ADDITION OF DRY ICE THROUGH ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Peyman Harirchi[1] and Mijia Yang[1]*

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ABSTRACT

The addition of dry ice as an admixture to cement pastes has many advantages such as improving the compressive strength and sequestration of CO2. However, its effect on the hydration mechanism of cement pastes is still unknown and will be investigated using electrochemical impedance spectroscopy (EIS) in this paper. Based on the linear correlation of cumulative hydration heat from the isothermal calorimetry test and the logarithm of high-frequency resistivity, a modified Knudson equation is derived. Corresponding hydration kinetic parameters are calculated by applying the boundary nucleation and growth (BNG) theory and kinetics model including Avrami, geometrical contraction, and diffusion equations. The boundary area per unit volume (O_v^B) for the control specimen and specimens with 0.2 % and 0.5 % cement weight dry ice addition is 0.1171, 0.1250, and 0.1562 respectively indicating that the dry ice addition increases the surface area of the nucleation process. In addition, the results show that the Avrami equation for monitoring the nucleation process is limited. Regarding the hydration curves, the transition from the nucleation and growth (NG) stage to the interaction of phase boundaries (I) stage is delayed by adding dry ice to the mixture.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DEEP LEARNING-BASED STRUCTURAL HEALTH MONITORING THROUGH THE INFUSION OF OPTICAL PHOTOS AND VIBRATION DATA

Saleh Al-Qudah[1] and Mijia Yang[1]*

[1]North Dakota State University

ABSTRACT

This paper reports an investigation of deep learning techniques in structural damage identification that can overcome the limitations of traditional visual inspection. First, a vibration-based deep learning model is established to locate the damage in a beam and a truss structure. Then an optical photo-based model is established and used to classify different defects. Based on the satisfactory outcomes of these two models, a new structural health monitoring technique is proposed through the infusion of optical photos and vibration data. Vibration signals and true structural images for a truss are used to demonstrate the capability of the proposed method. It was found that the infusion of vibration data and optical photos can enhance damage identification significantly and overcome incomplete vibration signals or blurred optical photo inputs.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONSTITUTIVE MODELING OF THE RATE-DEPENDENCY OF SAND DURING FLOWSLIDES

Ming Yang[1] and Giuseppe Buscarnera[1]*

[1]Northwestern University

ABSTRACT

A recently established multiscale framework coupling a sliding consolidation model with a local solver based on the discrete element method (DEM) suggests that the dynamics of flowslide runout in loose sand depends on two macroscale effects regulated by the shear rate: (i) the increased friction coefficient; (ii) the enhanced dilation. This contribution aims to develop a rate-dependent constitutive model capturing these behaviors observed in multiscale simulations. While the conventional viscoplasticity formulation of Perzyna-type, following the conceptual structure of Bingham model that adds a dashpot parallel to the plastic slider, effectively models the reduced runout distance, it is unable to reflect the rate-dependent nature of the friction coefficient (often referred to as mu(I) rheology), as seen both in experiments and DEM simulations of granular flow. To address this limitation, we propose an alternative conceptual structure reminiscent of an extended Kelvin-Voigt model. In this structure, both the spring and plastic slider are positioned in parallel to the viscous damper. This arrangement necessitates the partition of the total stress tensor into solid and rheological stress components. The solid stress corresponds to the standard effective stress of rate-independent plasticity models, and thus regulates the deformation of the spring and the plastic slider. The rheological stress is rate-dependent and obtained through the viscous damper, where the deviatoric part is collinear with the deviatoric strain rate, and the volumetric part is derived through thermodynamics, collectively giving rise to a compressible mu(I) rheology. The proposed constitutive model is shown to generate accurate simulation results under both drained and undrained simple shear simulations across a arrange of strain rates. Furthermore, it successfully reproduces the flowslide runout distance retrieved in DEM simulations and primarily regulated by the strain rate dependence of the material properties during the dynamic runout stage.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ORIGAMI VIA INSTABILITY

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ABSTRACT

Cylindrical shell structures made from soft materials undergo large deformations as pressurized. When subjected to a vacuum, these structures display a reversible buckling instability that mimics the kinematics of Kresling origami. In this study, we demonstrate that precise control of the geometry of thin-walled cylindrical shells leads to the emergence of distinct post-buckling deformation modes, including contraction, twisting, and bending. Leveraging these instability-driven deformations, we construct soft actuators capable of complex multimodal movements. The proposed design strategy is applied in both air and water, enabling soft manipulators that delicately pick up objects such as a fruit and a seashell using a simple vacuum.

Characterization and modeling of physical processes in porous materials across scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MICROPOROMECHANICS OF NON-ISOTROPIC INTERACTIONS AMONG PORES AND SOLID MATRIX

Yifan Yang[1], Dawei Xue[1] and Giuseppe Buscarnera[1]*

[1]Northwestern University

ABSTRACT

Non-isotropic interactions among primary and secondary minerals play a crucial role in subsurface geo-storage, including carbon sequestration enacted by mineralization reactions. To understand the role of such mineral transformations at the macroscopic scale of porous continua, an augmented poromechanical framework is developed based on the classical Biot's theory, thus focusing on the effect of isotropic stress-deformation effects stemming from the pores of the matrix. Applying micromechanics principles, the role of the stiffness ratio of both in-pore and matrix constituents is quantified by resolving explicitly the effect of the constitutive tensors of each unit and ensuring thermodynamic consistency. Casted in this form, it is shown that the framework can be coupled with thermal and chemical effects, i.e., two essential driving mechanisms in subsurface fluid storage operations. Furthermore, it is shown that by using an Eshelby elastic solution in conjunction with multiple types of homogenization schemes it is possible to specialize the macroscale constitutive law to non-isotropic interactions between the matrix and idealized ellipsoidal pores, either individual (dilute scheme) or interacting (Mori-Tanaka-Benveniste scheme). In this augmented framework the pore-scale loadings induced by physicochemical effects into the pores become equivalent to eigenstrains stemming from the secondary minerals produced by mineralization reactions. With this driving mechanism, a series of parametric analyses are carried out. It is finally shown that the mechanical properties of the secondary minerals significantly affect the magnitude of porosity change, matrix volumetric strain, and the potential for crack opening, all effects that are predicted to be nonlinear and that will play a role in the success of subsurface storage operations.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Data-driven methods and research for physical testing in structural engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MECHANICS-INFORMED DATA MODEL PREDICTION OF STEEL COLUMN STRENGTH CONSIDERING BUCKLING DEFORMATION AND INITIAL GEOMETRIC IMPERFECTIONS

Kai Chen[1], Cem Bartu Cevik[2], Cristopher Moen[3], Yile Wang[1], Yuchen Yang[1] and Zhidong Zhang[4]*

[1]Johns Hopkins University
[2]Robert College
[3]RunToSolve LLC
[4]University of Virginia

ABSTRACT

An XGBoost decision tree data model is trained and tested. The training data is generated by solving random samples of the classical ordinary differential equation for a simply-supported steel column with an initial sweep imperfection combined with a first yield stress interaction failure criterion consistent with the Perry-Robertson equation. Model accuracy is evaluated for different decision tree general, booster, and task parameters with the goal of establishing a model protocol that can be generally followed for mechanics-informed data models. Input parameter importance (column length, initial imperfection magnitude, and column section properties) is also quantified.

PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ROLE OF SUBSTRATE ROUGHNESS IN SOIL DESICCATION CRACKING

Yuhan Yang[1], Chao Zhang[1], Linyun Gou[1], Renpeng Chen[1] and Yi Dong[2]*

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ABSTRACT

Soil desiccation crack is ubiquitous in nature, yet the physics of its initiation and propagation is still under debate. Existing researches imply that the desiccation phenomenon is an outcome of highly coupled processes in multiphase media under multiple fields of mechanics, hydraulics, and even thermals. Such coupled physics occurring at multiple types of interfaces in soil gives rise to unprecedented complexities in soil desiccation. Here, an experimental attempt is made to uncover the role of substrate roughness, a commonly recognized key factor, in the soil desiccation process. The substrate roughness is deliberately fabricated by 3D printing, whereas the thickness of soil sample and environmental humidity are controlled to eliminate the effects of large hydraulic gradient. Four types of soils with varying expansibilities are desiccated on substrates with varying roughness. It reveals that: (1) soil desiccation crack evolution can be conceived as a competing process between the shear failure of the interface, i.e., slippage of the soil-substrate interface, and the tensile failure of soil, i.e., crack propagation, in minimizing the total energy of drying soil; (2) substrate roughness alters the failure mode and shear strength of soil-substrate interface and its sensitivity to moisture, thereby it regulates the pattern of how soil crack propagates in soil with varying expansibilities upon drying; (3) soil expansibility is recognized as a key factor governing the crack-initiation point in addition to the widely recognized air-entry, and flaws in soil are the sources for the crack angle of 120° and bimodal crack angle distribution.

MACHINE LEARNING FOR STATISTICAL MODELING OF FIBER-REINFORCED COMPOSITES DELAMINATION

Zhengtao Yao[1], Philippe Hawi[1], Venkat Aitharaju[2], Jay Mahishi[2] and Roger Ghanem[1]*

[1]University of Southern California
[2]General Motors

ABSTRACT

Delamination in fiber-reinforced composites is a critical area of study due to its impact on the structural integrity and life of composite materials. Achieving perfect contact between layers during the manufacturing process is challenging with any discrepancy potentially inducing delamination. This phenomenon can severely compromise mechanical performance and lead to catastrophic failures in critical applications such as aerospace and automotive industries. The mechanical behavior of a carbon-resin composite material under Mode I and Mode II fracture for use as automotive battery enclosure is explored in this work. Deep learning models are applied to understand and predict the delamination behavior of composites using Representative Volume Elements (RVE), a widely used conceptual and numerical device to explore the constitutive relationship of materials while soliciting information from their subscale, by describing the behavior at one material point of a physical device while homogenizing the local behavior over finer scales.

Specifically, a four-layer-stacked RVE is created and canonical tests of Modes I and II failure are set. Geometrical features within each RVE (e.g. radius ratio and volume fraction) are specified as random variables with Beta distributions. Material properties within each RVE, including strength and stiffness of the resin, tows, and cohesive layers are specified as independent Beta-distributed random variables. A total of 2000 RVE simulations, with samples drawn from the above Beta-distributions, are conducted for laminae tearing (ZZ strain) and shearing (XZ strain), with tows in fixed tension and in compression strain load. Intermediate results such as stress history and energy history of the components are extracted and used for training the ML models. A quadrature failure envelope of the strain combination is captured, and it is found that tension RVE has a higher max strength combination and compression will cause deterioration of the delamination strength, in both ZZ and XZ directions.

PCA (Principal Components Analysis) is used to eliminate spurious discontinuities and accelerate predictions of the stress-strain curve via dimension reduction. It is worth noting that 10 principal components out of 100 contain 99% of the variance for six directions of stresses history. A good match between predictions and ground truth is found using PCE (Polynomials Chaos Expansion) and neural network as machine learning models, for delamination constitutive relationship, both in linear and nonlinear (deterioration) regime of the stress-strain curve. A user-defined subroutine is developed in LS-Dyna to explore the multiscale analysis using this method to verify its accuracy.

CONCEPTUAL DESIGN AND PRODUCTION OF LIGHTWEIGHT TWO-STAGE CONCRETE COMPOSITES

Fan Zheng[1] and Hailong Ye[1]*

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ABSTRACT

With the development of building information modelling (BIM) and the increase in labour costs, modular integrated construction (MiC) which adopts the concept of factory assembly followed by on-site installation is a promising trend. For MiC projects, the application of lightweight concrete can increase the efficiency of transportation and lifting. Using lightweight aggregates to replace normal aggregate is a common strategy for designing lightweight concrete. However, the mechanical strength of concrete is compromised by the segregation and lower strength of lightweight aggregates. In this work, a lightweight concrete composite for structural applications was designed and produced. The concept of two-stage concrete was introduced for casting to prevent segregation of lightweight aggregates. A vacuum-assisted slurry infiltration setup was designed and assembled, in which the lightweight aggregates were preplaced in the mould and then the slurry was poured to fill the voids between the aggregates. Foam glass with a size range of 10-20 mm and a crushing strength around 10 MPa was used as lightweight aggregates to replace normal aggregates by different volume proportions. The slurry used was a lightweight ultra-high performance concrete (UHPC), which can reduce the composite density and compensate for the strength reduction caused by lightweight aggregates. By using different combinations of lightweight UHPC and lightweight aggregates, lightweight concrete composites with various strength grades can be designed. The proposed casting setup for lightweight two-stage concrete composite production at the element scale can be implemented in the prefabrication factory.

PMC - General Session

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

STATISTICAL EVALUATION OF GEOMETRICAL MICROVOID CHARACTERISTICS THAT INITIATE ULTRA LOW CYCLE FATIGUE FRACTURE

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ABSTRACT

Structural steel members and connections may experience ultra-low cycle fatigue (ULCF) loading during earthquakes. Field observations and laboratory tests of structural steel connections and full-scale steel structures indicate ductile fracture as the fracture-initiating mechanism under ULCF loading. Ductile fracture under ULCF is dependent on the strain amplitude which is usually large, the number of cycles which is less than 100, and the evolving stress state and total plastic strain. Stress triaxiality and Lode parameter are the dimensionless quantities explored by researchers to quantify the stress state. Microvoid coalescence initiates ductile fracture and the geometric void configuration at the instance of ULCF fracture is not explored yet. The present study aims to geometrically characterize the microvoids experimentally at the instance of fatigue fracture and determine their relationship with the quantities that describe the state of stress and strain in the fracture specimens.

In the present study, ULCF tests were conducted on axisymmetrically notched ASTM A992 structural steel specimens to achieve a wide range of high-stress triaxialities. High-resolution micrographs of the fracture surface of the test specimens were obtained using a scanning electron microscope. Subsequently, representative regions with 75µm × 75µm projected surface areas were randomly chosen on each micrograph and 25 microvoids were sampled from each of the representative areas. Statistical analysis was performed on the microvoid sizes extracted from the micrographs. To understand the relationship between stress triaxiality, plastic strain, and microvoid geometrical features, micrographs were extracted across the diameter of the fracture specimens. Non-linear finite element analysis was performed on the notched specimens to obtain the variation of stress triaxiality and equivalent plastic strain across the cross-section of the fracture surface. The relationship between the experimentally obtained microvoid geometrical features, stress triaxiality, and equivalent plastic strain will be discussed in the talk.

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL INVESTIGATION OF GRAIN SIZE SEGREGATION MECHANISMS IN DEBRIS FLOWS

Fan Yi[12] and Fernando Garcia[1]*

[1]University of Michigan
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ABSTRACT

Post-wildfire debris flows are increasing in frequency due to ongoing climate change and its effects on rainfall intensities and wildfire potential. The probability, runout path, and inundation depths of debris flow hazards are modeled well through various numerical means, but modeling of these effects typically requires homogenizing the solid debris into a single phase. The solid debris can range in size from fine silts to large boulders, the latter of which pose a unique impact hazard not associated with the finer debris or fluid phase. The boulders can destroy structures, block evacuation routes, and alter debris runout paths. Over long runout distances, the boulders segregate from the rest of the viscous debris to form a boulder-rich debris front. Coarse-grained lateral levees form as the advancing finer-grained debris pushes the coarser debris aside. Understanding of the mechanisms behind grain size segregation and lateral levee formation during debris flows is crucial for comprehending the full mechanics of debris flow runout. To accurately forecast the runout paths and potential impact energy of boulders, the boulders must be modeled as a discontinuous granular system. This study achieves the latter using the discrete element method to simulate the processes of grain size segregation and levee formation using two distinct particle types with different grain sizes. The simulation results are validated against physical experiments with different proportions of fine and coarse grains. The coarsest particles translate in a helical motion relative to the front of the flow due to velocity gradients along the depth and width of the debris. This motion is hypothesized from physical experiments but can be fully quantified via discrete element simulations. Factors such as grain size and shape distribution, basal boundary conditions, and interparticle contact properties are further explored to show the principal dependencies of grain size segregation. The roughness of the flume surface and the fluency of finer particles are shown to play the most pivotal roles in levee formation. The initial point of levee deposition and width of the coarse-grained levees are observed to be highly sensitive to the volume fraction of the coarse and fine grains. Further assessments will focus on evaluating how the scalability of grain size influences the motion of debris flows and how the simulation approach may be applicable to realistic terrain associated with debris flow case histories.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ESTIMATION OF UNKNOWN PARAMETERS AND HIDDEN PHYSICS WITH ADAPTIVE BASIS FUNCTION AND SUCCESSIVE CONVEX APPROXIMATION

Letian Yi[1], Siyuan Yang[1], Ying Cui[1] and Zhilu Lai[1]*

[1]The Hong Kong University of Science and Technology

ABSTRACT

Continuous spatiotemporal dynamic models are often represented by differential equations (ODEs or PDEs). In previous research, various surrogate models have been proposed to simultaneously fit measured data and satisfy differential equations to approximate the response process, including global and local function methods. However, the global function methods, typically represented by physics-informed neural networks (PINN), lack the necessary repeatability and robustness due to their sensitivity to initial parameter values and noise. On the other hand, the local function methods, represented by various basis functions, struggle to accurately fit data which have unevenly distributed geometric features, affecting the accuracy of parameter estimation and high-order derivatives. The proposed method adaptively adjusts basis functions according to the data feature distribution, thereby accurately approximating the solution of the differential equation. Additionally, the successive convex approximation (SCA) algorithm is introduced to solve nonconvex optimization problems arising from nonlinear differential equations, theoretically guaranteeing solution convergence. The proposed method is shown to effectively estimate parameters, approximate solutions, and solutions' high-order derivatives of various differential equations with considerable precision. The method combines scientific theories with detailed data information in a systematic manner to deduce the properties of the process from observed data.

Computational statistics for natural hazards engineering: Advances in uncertainty quantification, surrogate modeling, and dimension reduction for performance-based design of structures and systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GAUSSIAN PROCESS SURROGATE MODELING OF WIND PRESSURE STATISTICS OF TWO ADJACENT BUILDINGS

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ABSTRACT

Urban cities are vulnerable to the impact of dynamic wind effects. In predicting the wind load applied to the building surfaces, it is important to consider properly the interference from the surrounding building environment. In particular, such inter-building wind interference effect is often investigated through a series of wind tunnel experiments, repeated for different arrangements of buildings, their geometries, and wind directions. To interpolate the wind tunnel experiment database and to provide the outcome of unseen experiments, this research develops a surrogate model that can predict the wind-induced interference effect. We used the physical wind tunnel experiment dataset developed and shared by Tokyo Polytechnic University (TPU) to train a surrogate model, consisting of spatiotemporal pressure patterns measured at the surface of a building model located adjacent to another tall building model. In particular, a Gaussian process (GP) surrogate model is developed to predict the time-aggregated statistics - mean, standard deviation, and peaks of pressure coefficients - across the building surface for different building arrangements, building heights, and wind directions. To deal with high-dimensional output quantities of interest (representing the spatial pattern of each pressure statistic), the principal component analysis-based dimension reduction technique is introduced and coupled with GP formulation, and the results are compared with alternative GP formulations without dimension reduction. Different calibration objective functions and correlation kernel choices are investigated with numerical results. The unique discussion points include consideration of periodicity in the wind direction, selection of optimal GP calibration objective functions compromising among multiple output quantities, selection of appropriate validation metrics for multiple outputs with varying scales, average and quantile performances, and effect of different underlying noise levels in the observation dataset. Additionally, adaptive Design of Experiments (DoE) strategies are applied to guide the sequential design of wind tunnel tests, aiming at identifying the aerodynamically favorable and unfavorable wind scenarios and maximizing the information to train a surrogate model from a limited number of wind tunnel tests.

Failure and function in structural stability applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BUCKLIPHILIA TO THE RESCUE: PROTOTYPES FOR BUCKLING-DRIVEN SHADING SOLUTIONS

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ABSTRACT

Buckling and structural instabilities are generally considered as concepts to design against, rather than design for them. In numerous cases, erroneous assumptions or negligence of instability effects, have led to detrimental results and failures in structural engineering. As new computational tools able to perform nonlinear analyses become widespread, the emergence of new engineered materials has created new pathways, where a particular instability can be designed for, as an aspect of the multifunctionality of the particular structure. This concept is not new, it has already been considered for passive control of adaptive systems in the aerospace and automotive industries, in the form of Morphing Structures[1]. This has been further explored by Reis[2], defining this trend for designing for instabilities as “Buckliphilia”, in other words “buckling-“ or “instability-friendly” designs. In this work we explore different applications where “buckliphilia” emerges as a low energy solution to a particular problem and particularly through the investigation of prototypes of different strut configurations with buckling driven control for shading. Inspired by a reduced mechanical model for temperature adaptable facades[3] and the postbuckling behaviour of 3D printed struts[4], this contribution concludes by showing how buckliphilia prototypes tackling a particular problem could be used in a Stability class as a practical example for designing for instabilities.

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PMC - General Session
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECT OF DIFFERENT STRUCTURAL CHARACTERISTICS ON SEISMIC FRAGILITY CURVES OF REINFORCED CONCRETE FRAME BUILDINGS

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ABSTRACT

Multi-story reinforced concrete (RC) buildings, constituting the majority of building stock in Turkey, were significantly affected by numerous major earthquake events in the past, including the latest sequence of earthquakes that occurred in Kahramanmaras, Turkey on February 6th, 2023. The extensive damage and total collapse of these buildings can be attributed to inadequate designs that do not comply with seismic codes, low material quality, and poor construction practices. Meanwhile, aging effects such as corrosion in RC members can degrade section capacities and alter global dynamic characteristics of the structure, ultimately increasing its seismic vulnerability over its lifetime. The aim of this study is to assess the impact of various structural characteristics on the seismic fragility curves of typical RC frame buildings. Within this scope, a parametric study is conducted on building frames with different number of stories, considering both high-code and low-code seismic designs, increments in concrete compressive strength and different levels of steel reinforcement corrosion. The finite element models of the frames are subjected to nonlinear time-history analyses, and resulting demands are used to develop seismic fragility curves for each combination of building features. At the end of the study, critical structural features influencing seismic fragility are identified, and a discussion on determining the optimum service life of these types of buildings is presented. The fragility curves developed in this study can be utilized in frameworks for estimating regional damage and losses under given earthquake scenarios.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-PHYSICS LATTICE DISCRETE PARTICLE MODEL (M-LDPM) FOR THE COUPLING OF DIFFUSION PROCESSES AND FRACTURE

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ABSTRACT

In this study, a Multiphysics-Lattice Discrete Particle Model (M-LDPM) framework with the application for coupled fracture-pore flow problems has been formulated. The M-LDPM framework involves fully coupled dual lattice systems, named the LDPM tessellation and the Flow Lattice Element (FLE) network. The LDPM governing equations are revisited and imposed with the influence of the fluid pore pressure. The Flow Lattice Model (FLM) governing equations for pore pressure flow have been derived through the mass conservation laws within both uncracked and cracked volumes. The numerical implementation of LDPM utilizes the Abaqus explicit dynamic user element subroutine VUEL, while the FLM implementation utilizes the Abaqus implicit transient user subroutine UEL. The data communication in M-LDPM coupling is implemented using the operating system Interprocess Communication (IPC) mechanism which exchanges information between the two Abaqus solvers that run as two independent processes. The M-LDPM framework enables seamless coupling of the mechanical and diffusion/flow behavior of the material at the aggregate scale. As a result, the variation of conductivity and permeability induced by fracturing processes can be simulated by formulating the transport constitutive laws of the flow elements as functions of local crack conditions. The validity of the M-LDPM framework is tested by comparing the numerical simulation results with analytical solutions of classical benchmarks in poromechanics.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SINGUM MODELING OF MULTISCALE AND MULTIPHYSICAL BEHAVIOR OF LATTICE-BASED MATERIALS

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ABSTRACT

Lattice materials formed by springs or bonds with connection nodes are common in 3D printing metamaterials or crystal structures. When short-range interactions between the nodes are considered, the effective material behavior depends on the interaction nature and the lattice structure. The recently developed singum model transfers the force-displacement relationship of the springs in the lattice to the stress-strain relationship in the continuum particle of singum, and provides the analytical form of tangential elasticity. When a pre-stress exists in the lattice, the stiffness tensor significantly changes due to the effect of the configurational stress. The anisotropy and asymmetry of the stiffness tensor for some unique lattice structures are demonstrated. The singum model can be extended to multiphysical behavior of lattice-based materials. The effective thermal conductivity of a granular lattice is predicted.

Assessing human-infrastructure interactions and their performance
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

VISION-BASED MONITORING FOR PEDESTRIAN SUSPENTION BRIDGES

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ABSTRACT

Recently, numbers of long span pedestrian suspension bridges have been constructed worldwide. While recent tragedies regarding pedestrian suspension bridges have shown how these bridges can wreak havoc on the society, the current practice for maintenance for the pedestrian suspension bridges are not being done efficiently. This study presents a new vision-based structural health monitoring system for pedestrian suspension bridges. The proposed system estimates the location and the magnitude of the pedestrian load, as well as the dynamic response of the pedestrian bridges by utilizing artificial intelligence and computer vision techniques. A simulation-based validation test and on-site validation tests was conducted to verify the performance of the proposed system.

EXPERIMENTAL INVESTIGATION OF HIGHLY TURBULENT WIND FIELD EFFECTS ON SPHERICAL DEBRIS FLIGHT

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ABSTRACT

A highly turbulent wind field can significantly impact the flight trajectories of windborne debris and hence the risk of damage to building envelopes. Faithfully simulating complex debris flight behaviors in a realistic three-dimensional (3D) turbulent wind field using numerical simulations can be very challenging due to both accuracy/efficiency issues. Wind tunnel testing may be a viable approach to investigate the windborne debris flight characteristics. Existing wind tunnel studies on debris flight usually fail to properly scale the debris and accurately generate a highly turbulent wind field that reflects realistic urban wind conditions. In addition, the impacts of the source building (where debris is released) and the target building (where debris hits) on the wind field and debris flight trajectory have not been quantitively studied in the existing literature. This study systematically investigates the wind field impact on spherical debris flight in the Boundary Layer Wind Tunnel at the University of Florida. The building and debris are scaled to properly represent the full-scale prototype. To accurately model turbulence scale and intensity, an array of actively controlled fans are utilized to recover the low-frequency energy deficit in wind turbulence resulting from conventional passive devices. High-speed cameras equipped with computer vision techniques track the 3D flight trajectory of properly scaled debris in a realistic turbulent wind field. The impacts of low-frequency wind turbulence, wake flow past source building, and distorted flow before target building are discussed in detail. This study provides valuable data for revealing the mechanisms of complex debris flight behaviors in highly turbulent winds and validating numerical models for windborne debris flight.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NEURAL NETWORKS WITH KERNEL-WEIGHTED CORRECTIVE RESIDUALS FOR INVERSE DESIGN

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ABSTRACT

Topology optimization is a challenging inverse problem as it is high-dimensional and usually constrained by partial differential equations (PDEs) and additional inequalities. Recently, Physics-Informed Neural Networks (PINNs) have been employed to simplify this process, but they struggle to manage all design requirements and their effectiveness largely depends on network configuration. To address these challenges, we leverage neural networks (NNs) with kernel-weighted Corrective Residuals (CoRes) for topology optimization. We have recently developed NN-CoRes to integrate the strengths of kernel methods and deep NNs. In this presentation, we show that they greatly help in (1) satisfying equality constraints in the design problem, and (2) simplifying the inverse design by decreasing the sensitivity of NNs to factors such as random initialization, architecture type, and choice of optimizer.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

BRUCITE CARBONATION: MOLECULAR INSIGHTS AND SUSTAINABLE CARBON CAPTURE

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ABSTRACT

Mineral carbonation as a viable strategy for carbon capture and storage (CCS) has gained considerable attention in recent years. Often found in serpentine deposits and hydrothermal veins, brucite ($Mg(OH)_2$) has emerged as a promising solution for carbon mineralization due to its abundance and potential for sequestering carbon dioxide. This study employs molecular dynamics simulations and enhanced sampling methods to delve into the intricacies of brucite carbonation by studying crucial aspects of this process such as bicarbonate formation, magnesium carbonate nucleation, and water exchange around magnesium atoms.

Investigating the formation of bicarbonate species reveals the complex details of the initial stages of carbonation, providing fundamental insights that are crucial for optimizing carbon capture processes. This process is influenced by kinetic barriers related to the activation energy required for the conversion of dissolved carbon dioxide into bicarbonate ions. The lack of an appropriate reactive Force Field has been an obstacle for achieving this goal. Bicarbonate, as an intermediate product, eventually transforms into stable carbonate minerals through various mineralization reactions. These carbonate minerals effectively trap and immobilize CO_2 by preventing its release into the atmosphere. Also, by scrutinizing the magnesium carbonate formation through the formation of a stable nucleus, we aim to contribute to the development of strategies for controlled mineralization, enhancing the technological efficiency of brucite-based carbon capture.

Furthermore, in trying to understand the dynamic behavior of water molecules surrounding magnesium atoms, the water exchange dynamics have been studied to explain the role of hydration in the carbonation process. The coordination of water molecules and their stability in the hydration shell affect the overall reactivity of magnesium hydroxide with carbon dioxide, influencing the kinetics and thermodynamics of the reaction. This knowledge would be instrumental in designing interventions to accelerate or decelerate the carbonation rate as needed for practical applications.

The importance of this research extends beyond the realms of fundamental science. Harnessing brucite carbonation for carbon capture not only addresses the global challenge of mitigating anthropogenic CO_2 emissions but also holds the potential to revolutionize the landscape of sustainable energy technologies. The scalability and cost-effectiveness of brucite, coupled with the insights gained from our molecular-level investigations, position this mineral as a cornerstone in the development of environmentally friendly CCS solutions.

ENHANCING THE RESILIENCE OF LARGE-SCALE INFRASTRUCTURE NETWORKS USING GNN-ENHANCED DEEP REINFORCEMENT LEARNING

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ABSTRACT

Infrastructure systems play a critical role in ensuring socio-economic prosperity and public safety. As such, it is imperative to rapidly restore damaged infrastructure systems in the aftermath of disruptions. During restoration management, decision-makers in infrastructure systems face the challenge of optimizing the dispatch of multiple repair crews and network flow over the restoration horizon. However, this task is an NP-hard problem that cannot be solved exactly using polynomial time algorithms.

This study develops a GGN-enhanced deep reinforcement learning framework to optimize the resilience of large-scale infrastructure networks. This model integrates graph neural network (GNN) into deep reinforcement learning (GNN-DRL): the GNN model is designed to learn a more effective embedding of the infrastructure network while the DRL model is trained to optimize repair decisions and network flow. Specifically, the GNN model encodes essential information about the network using inputs such as topology and performance of service nodes and then outputs learned characteristics of the networks, including a more effective representation of node and link features as well as network state evolution. These learned characteristics are then fed into the DRL model to improve its performance, which enables the search for optimal solutions in a prohibitively large action space.

While several studies have explored the application of DRL to enhance the resilience of infrastructure networks, most of these efforts have oversimplified crucial aspects of the restoration problem. For example, some have simplified the dispatch of repair crew or omitted the design of the optimal network flow, thereby constraining their practicality. To better mimic real-world distribution networks, our model incorporates Kirchhoff's current law for nodes (flow conservation) and voltage law for links (linear scaling of flow with potential drop). Notably, the proposed model also addresses the dispatch of multiple repair crews at the same time step. Furthermore, our model considers the relative significance of service nodes and accommodates changes in user demand following disruptions. To handle large-scale networks, the model is trained using both small synthetic and real-world infrastructure networks and then applied to various large-scale application scenarios.

To validate the GNN-DRL model, extensive simulations are conducted across various real-world and synthetic large-scale infrastructure networks affected by multiple hazard scenarios. The proposed model is compared against multiple heuristic optimization approaches (e.g., greedy algorithms, genetic algorithms, and simulated annealing) in terms of solution quality and efficiency. Results indicate that the GNN-DRL model outperforms alternative approaches, leading to higher system resilience.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

NUMERICAL SIMULATION OF FLOW, SETTING, AND HARDENING OF 3D PRINTED CONCRETE

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ABSTRACT

3D printed concrete as an innovative construction technology has been increasingly used for intricate and customized structural designs. This requires an improved comprehension of the material properties' transition from the flow stage to solidification in concrete. The primary objective of this study is to simulate the various phases of 3D-printed concrete, including the flow, setting, and hardening stages, and validate the modeling method. The fresh concrete was simulated using smoothed particle hydrodynamics (SPH) coupled with the discrete element method (DEM). DEM was employed to represent the aggregate, capturing the movements of discrete particles, while the SPH was utilized to simulate the cement paste, modeling the continuous property of the concrete mixture. After the concrete setting, the lattice discrete particle model (LDPM) was used to model the failure behavior of concrete at the meso-scale. The concrete setting process, which depicts the transition of concrete from a viscous fluid to a solid state, was also simulated. The evolution of material properties during the concrete setting was provided by experimental tests. The entire simulation was performed in Project Chrono which is an open-source multi-physics engine. The simulation was validated by comparing the numerical results with the experimental data of real 3D printed concrete.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IDENTIFICATION OF STRUCTURAL PROPERTIES FROM LVD MEASUREMENT OF A STEEL RAILWAY BRIDGE

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ABSTRACT

Steel railway bridges are durable transportation infrastructure systems designed by allowable fatigue life, strength, and deformation response. With proper maintenance, their lifespan can be more than 100 years. During the long period of their service life, their deterioration rate needs to be updated by field data to avoid sudden failures from happening. The objective of this research is to present an approach to extract the structural properties (mass, damping, stiffness) of steel railway bridges using a single-point laser doppler vibrometry (LDV) from field data. A more-than-75-year-old steel railway bridge was measured by a portable continuous wave infrared (CWIR) LDV system at the midspan of the bridge to collect the dynamic displacement responses with (forced vibration) and without (free vibration) the train loading. Issues with modal coupling in the spectrum response were addressed before extracting damping ratio from the time-domain displacement response. A bounding approach was developed to estimate the ranges of fundamental mass, damping, and stiffness values of the bridge, as well as the train speed, to address the uncertainties in locomotive and passenger car weights.

Advances in modeling of material damage and fracture
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REMOTE TRANSIENT ELECTROMAGNETIC SCATTERING RESPONSE OF FRACTAL CRACKS IN MULTI-PHASE BRITTLE MATERIALS

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ABSTRACT

Cracking in multi-phase brittle materials such as Portland cement concrete is the main cause for jeopardizing the integrity, durability, and sustainability of the materials. Due to the heterogeneity of the materials, formation and development of cracks are manifested by three-dimensional irregular and complex shapes that may be described by fractal geometry. While surface cracks on brittle materials can be visually detected and mapped, their subsurface geometry is very challenging to be measured without destructive means. In this presentation, we present a simulation study on the transient electromagnetic (EM) scattering response of fractal cracks in brittle materials, using the finite difference time domain (FDTD) method. Different dimensions of Julia set fractals were introduced to a two-dimensional (2D) material model simulated by lossless dielectrics. A modulated Gaussian incident signal (point source) with a center frequency ranging from 8GHz to 18GHz was used to illuminate the cracked model. EM scattering response was collected by a circular antenna array in the simulation domain to study the radar cross section (RCS) (or radiation pattern) of each fractal crack. From our simulation work, it is found that the RCS of each fractal crack is sensitive to crack development, suggesting the importance of polar difference in the application and data interpretation of EM sensors (e.g., ground-penetrating radar and synthetic aperture radar) on concrete structures.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

PARTITION MODELING AND HETEROGENEOUS SOLUTION OF 3D TRAIN-TRACK-BRIDGE COUPLED SYSTEM SUBJECTED TO EARTHQUAKE EXCITATIONS

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ABSTRACT

As the computational complexity of practical engineering systems under environmental effects increases significantly, such as a 3D train-track-bridge coupled time-varying system considering random wheel-rail contact and earthquake excitations, how to efficiently and accurately solve and evaluate complex dynamic systems has garnered considerable attention. This study proposed a non-iterative partitioned computational method with the energy conservation property to efficiently resolve complex dynamic problems. The proposed method is composed of two computational modules: multi-partitioned structural analyzers and an interface solver, providing a modular solution for time-variant systems. A nonlinear time-varying mechanical model for the earthquake-TTB system, as an illustrated three-subsystem example, is established to demonstrate the method. Specifically, a 3D multi-train model considering a single train with 42 DOF and nonlinear wheel-track forces is constructed as a train subsystem. The rail-sleeper-ballast system is established as a track subsystem, and a typical multi-span continuous prestressed concrete simply supported beam bridge is built as a bridge subsystem. Track irregularities are regarded as stochastic excitations within the system, and 120 practical ground motion records with different combinations of magnitude-source-to-site distance (M-R) and earthquake intensity characteristics are selected as the external excitations. The application of the proposed method to address the partitioned system involves a comparative evaluation against various methods, including iterative approaches, highlighting its superior performance. Meanwhile, diverse scenarios regarding various combinations of vehicle speeds and track irregularity levels are defined in the analysis. Numerous nonlinear time-history analyses are conducted to evaluate the system comprehensively. Results indicate that the proposed method eliminates the necessity for time-variant matrix formation and the utilization of complex iterative procedures in partitioned computations, which significantly improves computational efficiency.

Cementitious materials: Experiments and modeling across the scales
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CEMCAT: CEMENTITIOUS MATERIALS CATALOGUE WITH THEIR COMPOSITIONS, PROPERTIES, SYNTHESIS AND CHARACTERIZATION METHODS, AND APPLICATIONS

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ABSTRACT

Cement is an essential construction material with complex chemistry and properties. The research advancements aim to enhance concrete's mechanical, chemical, and thermal properties. Sustainability is another aspect of cementitious materials that govern their practical applications. Researchers have reported numerous compositions of cementitious materials, their microstructure, properties, applications, synthesis and characterization methods through rigorous simulations and experiments. Some databases exist, like the NCSU concrete database1, the NIST database2, and a recent database3 of 279 compositions of supplementary cementitious materials collected from 107 research papers. In this work, we propose CemCat, a database of cementitious materials created through automated literature mining methods built on MatSciBERT (the world's first materials domain language model) and DiSCoMaT (graph neural network-based pipeline from extraction materials compositions from research paper tables). CemCat currently has ~20,000 compositions obtained from the research papers using DiSCoMaT. There are ~40,000 papers in the database from which various named entities like materials, synthesis and characterization methods, properties, and applications are extracted using MatSciBERT. This database aims to provide information about existing materials, their applications, properties, and manufacturing methods, allowing researchers and industries to gain insights into making sustainable concrete. In the presentation, we will discuss the information extraction tools (MatSciBERT and DiSCoMaT) used in this work and provide statistics about different aspects of the database, which will be helpful for the advancement of research for construction materials.

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THERMO-CHEMO-RHEOLOGICAL MODELING OF DIRECT INK WRITING BASED ON FRONTAL POLYMERIZATION

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ABSTRACT

Conventional manufacturing processes for thermoset polymers and composites typically involve continuous heating in an autoclave, which is an energy intensive and costly procedure. In recent years, frontal polymerization direct ink writing (FP-DIW) has emerged as a promising technique for the freeform manufacturing of polymeric structures with minimal energy requirements and no post-processing [1]. FP leverages heat diffusion and an exothermic reaction to propagate a self-sustaining polymerization front that cures a liquid or gel monomer, such as dicyclopentadiene (DCPD), into a solidified polymer. This technique is amenable to additive manufacturing by extruding a gel ink from a nozzle and utilizing FP to cure the material in its unsupported configuration. Of critical importance in this process is the effect of both mechanics and chemistry on the dimensional accuracy of the printed structure. The gel exhibits nonlinear viscoelastic properties as evidenced by shear thinning and die swell, and these properties evolve over time during the gelation process. The process parameters must be calibrated to ensure the extruded material cures before experiencing excessive deformations. Computational tools have recently been developed to predict the effect of process parameters on the dimensional accuracy of the printed part, accounting for both the rheology of the extruded material [2] and the solid-like behavior of the cured part [3]. In this talk, we first describe the thermo-chemo-rheological model that has been used to capture the effect of process parameters, material properties and environmental conditions on front propagation and the shape of axisymmetric structures printed through FP-DIW. We then discuss recent progress in implementing this model in 3D and the effect of rheological properties on the deformation of the extruded material. Lastly, we present on the application of FP-DIW to printing unidirectional carbon fiber tows and the multiphysics modeling approach used to study this process.

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Data-scarce modeling in engineering mechanics: Probabilistic learning, information maximization & transfer learning
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CONSTRAINED COST-AWARE MULTI-FIDELITY BAYESIAN OPTIMIZATION

Zahra Zanjani Foumani[1], Amin Yousefpour[1] and Ramin Bostanabad[1]*

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ABSTRACT

Bayesian optimization (BO) is a widely used technique for finding materials with unprecedented properties. However, relying solely on expensive high-fidelity (HF) sources can inflate optimization expenses in complex scenarios. To address this challenge and incorporate known and unknown constraints, we introduce a novel constrained cost-aware multi-fidelity BO (C2-MFBO) framework with a few novelties. Firstly, it uses manifold-embedded Gaussian process (GP) for emulation which handles mixed input spaces and models source-dependent noise and global trends. Secondly, it leverages a composite acquisition function (AF) that quantifies the information value of high- and low-fidelity sources differently and also accommodates source-dependent constraints. Through analytical and real-world examples, we will demonstrate the benefits of our approach which is publicly available via the GP+ package in Python.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

FEATHER-INSPIRED ARCHITECTED MATERIALS WITH SHAPE MEMORY

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ABSTRACT

The keratinous materials in the calamus section of avian feather shafts exhibit outstanding mechanical properties, providing strength, toughness, and inherent lightweight characteristics crucial for supporting aerodynamic functions during flight. Recent reports have also confirmed the role of shape memory properties in feather shafts, playing a crucial role in preventing permanent damage that might compromise the structural integrity of the feathers. In our study, we focus into the mechanisms driving these shape memory properties using mechanics and simple models, with a specific focus on the synergistic interplay between the matrix—an amorphous phase that absorbs water and undergoes inelastic deformation under severe stress—and the fibers—intermediate keratin filaments rich in crystalline domains resilient to hydration. Our preliminary analysis emphasizes the role of matrix swelling and softening due to hydration. Building on these insights, we develop a simple design concept and establish a mathematical framework for crafting bioinspired shape memory architected materials. In this talk, I will explain the conceptual framework and how these principles are put into practice through architected materials in such a way that these materials can be used for morphing and/or actuation.

Mechanics of wood and wood-based materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CHARACTERIZATION OF MECHANICAL PROPERTIES OF FIVE HOT-PRESSED LIGNINS EXTRACTED FROM DIFFERENT FEEDSTOCKS BY MICROMECHANICS-GUIDED NANOINDENTATION

Luis Zelaya-Lainez[1], Michael Schwaighofer[1], Markus Königsberger[1], Markus Lukacevic[1], Sebastian Serna-Loaiza[1], Michael Harasek[1], Anton Friedl[1] and Josef Füssl[1]*

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ABSTRACT

Lignin is a pivotal constituent of wood, ranking as the second most prevalent organic material globally. The escalating demand for sustainable and renewable resources propels the exploration of innovative applications for technical lignins, such as their integration as a matrix in bio-composites. Nevertheless, the pursuit of modeling these bio-composites hinges on precisely identifying lignin's mechanical properties, which remains relatively elusive. Complicating matters further is that technical lignins sourced from lignocellulosic materials exhibit notable disparities in their chemical composition, size, cross-linking, and functional groups. These variations arise from discrepancies in the raw materials and the isolation methods employed, including the pulping process and subsequent isolation and purification techniques. Hence, it becomes imperative to address these disparities when evaluating and understanding the mechanical characteristics of lignin. To tackle this challenge, our study examines five distinct hot-pressed lignins derived through diverse extraction processes from varying feedstocks. The assessment employs microscopy-aided grid nanoindentation, aiming to unravel the nuanced mechanical properties of these lignins. Through such meticulous investigation, we endeavor to contribute valuable insights that will aid in comprehending the intricate interplay between lignin's structural variations and its mechanical behavior. The derived mechanical properties exhibit a robust correlation with the porosity observed in the lignin specimens. This correlation finds an apt description through the Mori-Tanaka homogenization scheme within the framework of continuum micromechanics. Employing this micromechanical model, we conducted a reverse calculation to determine the stiffness of "solid" lignin devoid of pore influence, revealing Young's modulus of 7.12 GPa. The noteworthy alignment between the micromechanics model and the experimentally measured indentation modulus validates that the indentation modulus of solid lignin remains consistent across all five variants. Remarkably, this consistency holds irrespective of the extraction process or the specific feedstock employed.

OPTIMIZATION OF VOIDED POST TENSIONED SLABS

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ABSTRACT

Concrete, a major contributor to global CO2 emissions, necessitates enhanced structural efficiency to mitigate environmental impact. Given that a substantial portion of concrete in buildings resides in floor slabs, reducing concrete volume in slabs emerges as a central strategy to curtail overall consumption. Voided slabs, featuring embedded void elements, demonstrate increased structural efficiency by minimizing concrete consumption. Recent advancements highlight the superior performance of post-tensioned (PT) voided slabs, leveraging reduced cross-sectional voided areas to require fewer cables compared to solid PT slabs.

Structural optimization is a design tool that converts a structural design problem to a constrained minimization problem, solves it with mathematical programming tools, and has been shown to improve the efficiency of the structural design. However, existing studies typically focus on either optimization of voided slabs or PT slabs. Thus, in this study we present combined optimization of voided PT slabs, where the parametrization includes both geometrically rich cable layout and the voids distribution. Moreover, we extend existing studies on PT optimization in slabs by adding the number of tendons in each cable within a gradient-based framework. The results show notable savings both in concrete and in PT steel, resulting in significantly lower carbon footprint than traditional structural slab systems.

Computational fluid dynamics (CFD) and fluid-structure interaction (FSI): Method development and applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COMPRESSIBLE EULER FLOW COMPUTATIONS USING THE SHIFTED BOUNDARY METHOD

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ABSTRACT

In this talk we present the Shifted Boundary Method (SBM) for inviscid compressible flow computations in complex geometries. The Shifted Boundary Method belongs to the class of unfitted finite element methods. It reformulates the original boundary value problem over a surrogate (approximate) computational domain that does not have to be conformal to the true geometry; and accuracy is maintained by modifying the original boundary condition using Taylor expansions. Because SBM avoids integration over cut cells, it does not suffer from small time-step issues and allows efficient explicit time integration. Previously the SBM has been applied to solve the Poisson equations, Stokes flow equations, and viscous incompressible flows on complex domains, and in this talk we detail the derivation of SBM for more complex wave structures for Euler equations.

In addition to the general methodology derivation and numerical verification, we also discuss the advantages the SBM offers in avoiding spurious numerical artifacts in two scenarios: (a) when curved boundaries are represented by body-fitted polygonal approximations and (b) when the Kutta condition needs to be imposed in immersed simulations of airfoils.

Uncertainty characterization and propagation in complex nonlinear structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN PROJECTION PURSUIT FOR UNCERTAINTY QUANTIFICATION AND SURROGATE MODELING IN HIGH-DIMENSIONAL AND DEPENDENT PARAMETER SPACES

Xiaoshu Zeng[1] and Roger Ghanem[1]*

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ABSTRACT

Uncertainty quantification (UQ) and prediction for complex engineering systems pose two significant challenges: the curse of dimensionality stemming from high-dimensional parameter spaces and the necessity to handle dependent parameter spaces. While Polynomial Chaos Expansions (PCE) present a robust approach, their effectiveness relies on independent standard Gaussian variables. In our prior work, we introduced Projection Pursuit Adaptation (PPA) to efficiently construct PCE models, addressing the curse of dimensionality even with limited Monte Carlo (MC) data. This study targets the challenge of dependent parameter spaces through a data-driven approach. PCE relies on independence, and in scenarios with modest dimensions, methods like the Rosenblatt transformation can decouple dependent variables. However, this method necessitates joint distribution information, posing challenges in high-dimensional spaces. To address this, we propose using multivariate Regular Vine (R-vine) copulas to capture dependency structures within parameters. Subsequently, the Rosenblatt transformation enables bidirectional transformations between independent and dependent Gaussian samples. The R-vine copulas are integrated with the PPA method, establishing a unified framework for constructing optimally reduced PCE models tailored for high-dimensional problems with dependent parameter spaces. Our proposed methodology showcases remarkable accuracy in both UQ and prediction tasks, with the constructed PCE serving effectively as a surrogate model for machine learning regression. The efficiency of our approach is verified through applications of a borehole model and a space structure.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A CASE STUDY OF DETECTING SEGMENT JOINTS IN SHIELD TUNNELS USING RANGE IMAGES

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ABSTRACT

With the rapid pace of urbanization, subways that are typically housed in underground shield tunnels have gained popularity as an environmentally friendly mode of travel. Shield tunnels, as a prefabricated assembly structure, are prone to excessive deformation under the earth pressure over time. Therefore, it is crucial to monitor the structural deformation of subway tunnels to assess their reliability and guide their maintenance. High-precision technologies, such as Light Detection and Ranging (LiDAR) scanning for point clouds and close-range photogrammetry for high-definition images of a tunnel's internal surface, are currently employed to obtain operation and maintenance data. However, shield tunnels exhibit a structural weakness due to their segment joints. The rigid body movement of the joints contributes significantly more to the overall tunnel convergent deformation than the deformation of segments, but is often neglected. While the circumferential joints between adjacent segment rings can be easily identified from images via computer vision techniques, it is difficult to detect the longitudinal joints within the same ring due to interference of power pipelines or other facilities. Accurate localization of these joints within a ring is essential for calculating their rigid body movement from the point cloud. To address this issue, this study proposes a deep learning-based method for detecting segment joints within a ring using range images. A rotary scanning device with a depth sensor collected numerous range images of an operational shield tunnel's inner surface. These images were then analyzed to differentiate the depth features of segment joints from other installed facilities and equipment. A deep neural network based on the Encoder-Decoder architecture was constructed, with the collected range images as inputs, and the joint segmented images as outputs. The proposed method was compared to edge detection methods and traditional image segmentation models using the same dataset to assess accuracy and effectiveness. The results indicate that using range images for segment joint localization improves accuracy through enhanced feature extraction based on depth information. Additionally, by comparing to the traditional image segmentation method, the proposed deep learning model demonstrates better robustness in detecting longitudinal segment joints in real-world shield tunnels.

Keywords: Shield tunnel deformation; Segment joint detection; Range image; Deep learning; Encoder-decoder

Mechanics and physics of granular materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

EFFECTIVE STRESS AND POROELASTICITY THEORY FOR UNSATURATED SOILS INCORPORATING ADSORPTION AND CAPILLARITY

Chao Zhang[1], Shaojie Hu[1] and Ning Lu[2]*

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ABSTRACT

Adsorption and capillarity, in the order of high free energy to low, are the two soil–water interaction mechanisms controlling the hydro-mechanical behaviour of soils. Yet most of the poroelasticity theories of soil are based on capillarity only, leading to misrepresentations of hydro-mechanical behaviour in the low free energy regime beyond vaporisation. This inability is reasoned to be caused by two major limitations in the existing theories: missing interparticle attraction energy and incomplete definition of adsorption-induced pore-water pressure. A poroelasticity theory is formulated to incorporate the two soil–water interaction mechanisms, and the transition between them – that is, condensation/vaporisation, by expanding the classical three-phase mixture system to a four-phase mixture system with adsorptive water as an additional phase. An interparticle attractive stress is identified as one of the key sources for deformation and strength of soils induced by adsorption and is implemented in the poroelasticity theory. A recent breakthrough concept of soil sorptive potential is utilised to establish the physical link between adsorption-induced pore-water pressure and matric suction. The proposed poroelasticity theory can be reduced to several previous theories when interparticle attractive stress is ignored. The new theory is used to derive the effective stress equation for variably saturated soil by identifying energy-conjugated pairs. The derived effective stress equation leads to Zhang and Lu's unified effective stress equation, and can be reduced to Bishop's effective stress equation when only the capillary mechanism is considered and to Terzaghi's effective stress equation when a saturated condition is imposed. The derived effective stress equation is experimentally validated for a variety of soil in the full matric suction range, substantiating the validity and accuracy of the poroelasticity theory for soil under variably saturated conditions.

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TRAINING ACCURATE COMPUTER VISION BASED INFRASTRUCTURE DEFECT DETECTION MODEL UNDER ANNOTATION NOISE

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ABSTRACT

CV-based infrastructure defect detection is a highly data-centric application, where the labeling quality can be of crucial concern. Pixel-level labeling for image segmentation is a time-consuming but necessary job, often outsourced to third-party services. In the labeling process, noisy labels are unavoidable given that each annotator may have a different understanding of crack boundaries and even produce 'lazy' labels that contain large background areas. These noisy labels then confuse the model in the training process, by ignoring some complex crack geometry. In this talk, we will present a noisy learning framework to deliver accurate CV crack detection models under the influence of noisy labels. The effectiveness of the framework will be demonstrated on industrial-level real-world dataset created in the Hong Kong community.

Contributions of high-performing lightweight materials to sustainable development and infrastructure resilience of engineering systems

May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

SYNERGISTIC EFFECTS OF NANOPARTICLE GEOMETRIC SHAPE AND POST CURING ON CARBON-BASED NANOPARTICLE REINFORCED EPOXY NANOCOMPOSITES: CHARACTERIZATION, MICROSTRUCTURE AND ADHESION PROPERTIES

Dawei Zhang[1], Ying Huang[1] and Xingyu Wang[1]*

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ABSTRACT

Incorporating carbon-based nanoparticles and optimizing curing conditions are commonly recognized as two effective approaches of pursuing enhanced properties of epoxy nanocomposites. This study specifically explores the synergistic effects of nanoparticle geometric shape and post curing on carbon-based nanoparticle reinforced epoxy nanocomposites. Nanodiamonds (NDs), carbon nanotubes (CNTs), and graphenes (GNPs) with spherical, cylindrical, and planar geometric shapes are integrated in the epoxy matrix as 0-D, 1-D, and 2-D nanofillers, respectively. Epoxy nanocomposites with and without post curing are synthesized for each nanofiller and evaluated based on dispersion quality, viscosity, microstructure, and mechanical properties. Experimental results indicate that ND reinforced epoxy nanocomposites exhibit a more homogeneous nanoparticle dispersion, lower viscosity, reduced porosity, stronger adhesion properties, while CNT and GNP reinforced epoxy nanocomposites achieve higher tensile and shear strengths. In addition, post curing is proved to be effective in reducing porosity and improving mechanical properties of epoxy nanocomposites, but its effect becomes less pronounced with the addition of nanoparticles.

Molecular scale modeling and experimentation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENERGY RENORMALIZATION FOR TEMPERATURE TRANSFERABLE COARSE-GRAINING OF SILICONE POLYMER

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ABSTRACT

The bottom-up prediction of thermodynamic and mechanical behaviors of polymeric materials based on molecular dynamics (MD) simulation is of critical importance in polymer physics. Although the atomistically informed coarse-grained (CG) model can access greater spatiotemporal scales and retain essential chemical specificity, the temperature-transferable CG model is still a big challenge and hinders widespread application of this technique. Herein, we use silicone polymer, i.e., polydimethylsiloxane (PDMS), having a very low chain rigidity as a model system, combined with an energy-renormalization (ER) approach, to systematically develop a temperature-transferable CG model. Specifically, by introducing temperature-dependent ER factors to renormalize the effective distance and cohesive energy parameters, the developed CG model faithfully preserved the dynamics, mechanical and conformational behaviors compared with target all-atomistic (AA) model from glassy to melt regimes, which was further validated by experimental data. With the developed CG model featuring tremendously improved computational efficiency, we systematically explore the influences of cohesive interaction strength and temperature on the dynamical heterogeneity and mechanical response of polymers, where we observed consistent trends with other linear polymers with varying chain rigidity and monomeric structures. This study serves as an extension of our proposed ER approach of developing temperature transferable CG models with diverse segmental structures, highlighting the critical role of cohesive interaction strength on CG modeling of polymer dynamics and thermomechanical behaviors.

4M (modeling of multiphysics-multiscale-multifunctional) engineering materials and structures
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMIC RESPONSES OF VISCOELASTIC COMPOSITE BEAMS WITH SPHERICAL INCLUSIONS UNDER HARMONIC EXCITATION

Jinming Zhang[1], Chunlin Wu[2] and Huiming Yin[1]*

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ABSTRACT

This study explores the influence of particles in a viscoelastic particulate composite beam on its energy dissipation and natural frequency when subjected to external excitations. Utilizing Eshelby's equivalent inclusion method (EIM), the material mismatch is simulated by eigenstrains. The effects of particle interactions and boundaries are investigated through the inclusion-based boundary element method (iBEM). Spatial variations of eigenstrains are expressed in the polynomial-form based on the Taylor series expansions. The local stress field changing with time is solved through the domain and boundary integrals of the Green's function. Numerical case studies illustrate the effect of particles on the energy dissipation and natural frequency shifts of the viscoelastic system. A comparative analysis with a matrix without inclusions provides a comprehensive understanding of the complexities introduced by inhomogeneities. The findings highlight the substantial impact of microstructures on the dynamic behavior of the material, offering critical insights for design and analysis of composite materials under vibration environments.

Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TC-SINDY: A DATA-DRIVEN FRAMEWORK TO DISCOVER PHYSICS-BASED TROPICAL CYCLONE TRACK AND INTENSITY MODELS

Xi Zhong[1], *Wenjun Jiang*[1] *and Jize Zhang**[1]

[1]*Hong Kong University of Science and Technology*

ABSTRACT

Due to the limited historical tropical cyclones (TCs) records, it is critical to understand TC risk using large sets of synthesized TC events from statistics-based or physics-based TC track and intensity models. Physics-based models are often regarded as practically advantageous for their unique capability to represent basic physical principles and incorporate climate change impacts. However, formulating the physics-based models are not easy, commonly obtained by simple empirical formulas with inadequate performance.

Here, we present a simple yet powerful framework that distills physics-based TC models from historical TC data. By treating TC evolutions as dynamical systems, we discover the TC track and intensity governing equations from historical TC and environmental data via the Sparse Identification of Nonlinear Dynamics (SINDy) approach. Results show that our proposed TC-SINDy approach is able to identify parsimonious yet effective physics-based TC models. The identified models were applied to simulate TCs in the Western North Pacific (WNP) basin and the North Atlantic (NA) basin. Comparing against alternative models, our models agree better with historical records in terms of the prevailing tracks, the maximum sustained wind, and the statistics of key parameters (including the annual occurrence rate, translation speed, minimum approaching distance, and maximum tangential wind speed) along various kilo posts. Then, our proposed models were coupled with a widely used parametric wind field to obtain the probabilistic distribution of the surface wind. The results show that the estimated distributions are close to the historical histograms in two basins. Overall, it can be concluded that the proposed method presents a general data-driven framework for discovering physics-based TC models, enabling accurate TC simulations while reserving the capacity to accommodate the varying climate.

TC-DIFFUSION: A DEEP MARKOV-CHAIN TROPICAL CYCLONE SIMULATION MODEL WITH APPLICATION TO TYPHOON WIND HAZARD ANALYSIS

Wenjun Jiang[1]*, Xi Zhong*[1] *and Jize Zhang**[1]

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ABSTRACT

This paper introduces TC-Diffusion, a novel Markov-chain tropical cyclone full track simulation method. TC-Diffusion utilizes the recently proposed diffusion deep generative model, to enhance the accuracy and effectiveness of the Markov-chain simulations. Leveraging diffusion's exceptional capability to process high-dimensional inputs and conditions, our proposed TC movement and intensity model can effectively consider the TC state spatial heterogeneity without the need for segmentation or clustering. Additionally, it can incorporate various TC states to inform the simulated track and intensity change over the next 6 hours, all while maintaining the complexity of the underlying probability models. A synthetic 74-year TC dataset is simulated from the proposed full track simulation method to be compared against the historical TCs in the China Meteorological Administration (CMA) dataset. The results indicate that the developed model had strong performance in terms of matching the spatial distributions and landfalling statistics of historical TCs, even in TC-sparse regions. The developed full track model is ultimately combined with a parametric wind field to estimate wind hazards along the China southeastern coastline. Estimated design wind speed in multiple return periods generally agrees with those in the design code and alternative full-track methods. To summarize, this study allows for the application of diffusion models to enhance the simulation of TCs using a Markov-chain approach.

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ESTIMATING BUILDING-LEVEL SEISMIC DAMAGE THROUGH SELECTED STRUCTURAL MEMBERS

Milad Cheragh Zade[1], Shenghan Zhang[1] and Jize Zhang[1]*

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ABSTRACT

Advanced sensors, such as distributed fiber optic sensors, enable accurate damage measurements at the structural member level following disasters like earthquakes. However, it is often unfeasible to place sensors on every structural member within a building. Due to the complex and uncertain nature of building-level damage patterns, a criterion for selecting instrumented structural members is still lacking. This study introduces a novel probabilistic methodology for quantifying seismic damage, which utilizes information from selected members with sensor instrumentation (assuming known damage) to predict damage for the entire building. To demonstrate the framework, a reinforced concrete frame numerical model (based on the Van Nuys hotel) is employed, accounting for uncertainties in both material properties and input. We examine the physical damage evolution process for typical structural members and investigate damage correlations using a multi-output Gaussian process model. Based on this analysis, we propose an optimal selection procedure for instrumented structural members.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

WAVE PROPAGATION PROPERTIES IN GRANULAR MEDIA: RELATING ELASTIC WAVES TO MECHANICAL SIGNATURES

Li Zhang[1] and Jun Yang[1]*

[1]The University of Hong Kong

ABSTRACT

Wave propagation in granular materials and their mechanical behaviors are intrinsically intertwined. Whether we can predict shear-induced signatures of granular soils (e.g., fabric anisotropy) based on wave propagation properties and, if yes, what relationship can be obtained possess practical importance. The analytical framework would be promising in geotechnical applications as the wave velocity can be measured both in the laboratory and in the field. Here, we present a robust grain-scale model to propagate elastic waves along three principal stress directions through dense and loose randomly-packed granular assemblies. The varying extent of fabric anisotropy is obtained under a spectrum of triaxial stress states. Comprising hundreds and thousands of spherical particles, long specimens bounded by periodic boundaries are created to eliminate the near-field effect that brings uncertainties in determining wave velocity. The results show that variations of the wave velocity exhibit a positive correlation with the change of mean effective stresses and coordination numbers. A marked finding is that: wave velocity varies significantly along different propagating and vibrating directions owing to the anisotropic distribution of inter-particle contacts within a granular assembly. Moreover, a linear relationship can be established between the wave velocity anisotropy and fabric anisotropy.

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COUPLED THMC MODEL-BASED PREDICTION OF HYDRAULIC FRACTURE GEOMETRY AND SIZE UNDER SELF-PROPPING PHASE-TRANSITION FRACTURING

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ABSTRACT

The coupling of thermal, hydraulic, mechanical, and chemical (THMC) fields occurring during realization of self-propping phase-transition fracturing technology (SPFT) differs from those observed under geothermal development and carbon dioxide storage conditions, making it difficult to clarify the hydraulic fracture propagation pattern under the SPTF multifield coupling conditions. Based on the SPFT parameters and the physical/chemical characteristics of the phase-transition fracturing fluid system (PFFS), this study elaborated a set of THMC multifield coupling models. The algorithm comprehensively combining the finite element method, discretized virtual internal bonds, and element partition method (FEM-DVIB-EPM) was proposed and verified on the case study. The results show that the FEM-DVIB-EPM coupling algorithm can reduce the difficulty and improve the solving efficiency. Conventional fracturing fluid is used to form fractures, then PFFS is ejected to prop fractures, and finally, the displacement fluid is injected to replace all PFFS into the reservoir, which is the best injection mode. The length of the hydraulic fracture increases with the increase in the amount and displacement of PFFS, and excessive displacement may lead to uncontrolled fracture height. Under the parameters of the cases in this paper, the fracture length is not much different after the amount of PFFS exceeds 130 m3. When the displacement is 5 m3/min, a longer fracture length can be obtained under the condition of limiting excessive extension of the fracture height. This work helps reveal the mechanism of hydraulic fracture propagation caused by SPFT and provides a basis for hydraulic fracturing technology and treatment parameter optimization.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DISCRETE MODELS OF CONCRETE HETEROGENEITY

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ABSTRACT

Concrete heterogeneity plays a large role in determining its fracture behavior. In particular, the presence of aggregate particles within the cement-based matrix influences fracture and other properties of interest. By explicitly representing aggregate particles and their mechanical interactions, Lattice Discrete Particle Models effectively capture the role of heterogeneity during fracture processes [1]. Other discrete mechanical models of concrete, including alternative particle-based lattice models, account for heterogeneity in other ways [2]. This research employs Voronoi-cell lattice models (VCLM) to understand the various forms of heterogeneity that can be present within discrete modeling frameworks. For elastic stress analyses, which underpin the modeling of fracture, conventional lattice models simulate elastic behavior in a macroscopic sense. In a local sense, however, spurious fluctuations in stress occur, which can be regarded as a form of heterogeneity. Although this notional form of heterogeneity may have utility, it depends on discretization geometry and size. As described by Asahina et al. [3], the VCLM can be rendered elastically uniform for arbitrary settings of the elastic constants. Heterogeneity can then be introduced in a controlled manner by mapping, for example, spatially correlated distributions of stiffness and strength onto the lattice structure. Whereas this approach is effective for elastic stress analyses, the modeling of fracture involves additional considerations. Since the fracture criteria are formulated in terms of vectorial stress measures, which is a common trait of discrete modeling approaches, an additional form of heterogeneity appears. Here, too, there is a dependence on discretization geometry. The relative significance of the aforementioned forms of heterogeneity is investigated through the analysis of concrete fracture under various forms of loading.

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Multi-fidelity methods and machine learning for uncertainty propagation, inference, and optimization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTI-FIDELITY BAYESIAN OPTIMIZATION IN ENGINEERING DESIGN

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ABSTRACT

Resided at the intersection of multi-fidelity optimization (MFO) and Bayesian optimization (BO), MF BO has found a niche in solving expensive engineering design optimization problems, thanks to its advantages in incorporating physical and mathematical understandings of the problems, saving resources, addressing exploitation-exploration trade-off, considering uncertainty, and processing parallel computing. The increasing number of works dedicated to MF BO suggests the need for a comprehensive review of this advanced optimization technique. In this paper, we survey recent developments of two essential ingredients of MF BO: Gaussian process (GP) based MF surrogates and acquisition functions. We first categorize the existing MF modeling methods and MFO strategies to locate MF BO in a large family of surrogate-based optimization and MFO algorithms. We then exploit the common properties shared between the methods from each ingredient of MF BO to describe important GP-based MF surrogate models and review various acquisition functions. By doing so, we expect to provide a structured understanding of MF BO. Finally, we attempt to reveal important aspects that require further research for applications of MF BO in solving intricate yet important design optimization problems, including constrained optimization, high-dimensional optimization, optimization under uncertainty, and multi-objective optimization.

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IDENTIFICATION OF CREEP DAMAGE IN STRUCTURAL SYSTEMS USING PHYSICS-INFORMED PARALLEL NEURAL NETWORKS

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[1]The Pennsylvania State University

ABSTRACT

The identification of creep damage is critical for predicting the service life and ensuring the safety of structural systems subjected to long-term stress and environmental conditions. Recently, it has been demonstrated that Physics-Informed Parallel Neural Networks (PIPNNs) can be applied successfully and accurately to solve the inverse problems for the identification of structural systems. In this research, a significant extension of the PIPNNs framework is developed and demonstrated, addressing the specific challenges of identifying creep damage in structural systems based on limited and noisy sensor data. In this framework, based on continuum damage mechanics, the creep damage is represented as a continuous state variable throughout the structure. The creep deformation process is governed by a system of ordinary differential equations (ODEs), including an evolution equation for the damage state variables and a constitutive equation characterizing material damage behavior. In its general form, the ODEs are able to consider the various states of creep damage, that is the primary, secondary, tertiary and failure. The PIPNNs framework integrates sensor data, the governing mechanics equations, the boundary conditions of the structural systems, and the ODEs governing the creep damage evolution into the loss function of the neural network (NN) architecture. Through minimizing the physics-informed loss function, the NNs parameters and unknown initial damage state variables can be estimated. With the trained NNs, the full state of the structural system and the evolution of creep damage can then be estimated. The accuracy and validity of the damage identification PIPNNs framework are demonstrated by comparing its results to those obtained from closed-form analytical expressions when available and otherwise, the solution of the Ritz method for various structural systems. These examples include a two-column system and a two-span continuous beam, considering both concrete and metal materials and their associated creep damage evolution equations. The results consistently demonstrate that the PIPNNs framework can accurately estimate the evolution of creep damage within the structural system as well as being able to reconstruct the full state of the system based on the limited and noisy sensor data. Furthermore, for the studied inverse problems, the suggested PIPNNs framework was observed to be robust with respect to noise levels in the sensor data.

Recent advances in hybrid simulation and real-time hybrid simulation
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DYNAMIC CHARACTERIZATION OF ARCHITECTED METAMATERIALS USING REAL-TIME HYBRID SIMULATION

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ABSTRACT

Architected metamaterials are an emerging class of materials with extraordinary properties that can be tailored to achieve specific objectives by customizing their microstructural configurations. Further, the growth of additive manufacturing has enabled 3D printing of complex microstructures and has further stoked interest in this area. Applications areas of such architected metamaterials include mechanical, thermal, electrical, chemical, optical, magnetic and numerous others.

In this study, we focus on characterizing the dynamic performance of architected metamaterials such as energy absorption and wave attenuation under low velocity impact. We consider both, auxetic and nonauxetic microstructures, and study their response under plane wave propagation. A parametric study is conducted to evaluate how different microstructures perform and how their properties may be tailored to maximize wave attenuation.

A key objective of this study is to enable the use of real-time hybrid simulation (RTHS) for studying the dynamic characteristics of architected materials. With RTHS, that part of the metamaterial domain that is subjected to impact and undergoes large deformations and damage is modelled physically and other parts of the domain that remain linear are modeled numerically. A single actuator transfer system is used to connect the physical and numerical subdomains using an in-house Linux-based real-time execution platform. This effort is ongoing and challenges with conducting such RTHS and lessons learned will be presented.

Probabilistic, physics-guided, and multi-fidelity generative modeling for uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

CROSS ENTROPY ADAPTIVE IMPORTANCE SAMPLING USING AN EXPRESSIVE NON-PARAMETRIC MIXTURE MODELING APPROACH

Tianyu Zhang[1] and Jize Zhang[1]*

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ABSTRACT

Importance sampling is a pivotal technique for estimating failure probabilities in rare events, particularly in structural reliability analysis. IS efficiency highly depends on the quality of the chosen importance sampling density. Cross Entropy (CE) based Adaptive Importance Sampling (AIS) is recognized as an effective approach for identifying near-optimal sampling densities [1,2]. To advance CE-based AIS This study presents a new non-parametric Mixture model that aims to approximate the optimal IS proposal density. It combines the simplicity and parsimonious character of parametric approaches with the flexibility of non-parametric approach, and adapts the proposal based on failure sampling in the CE-guided manner. The resulting model underwent evaluation against a range of benchmark and engineering instances, and demonstrated superior performance in terms of efficiency and stability compared to current baselines. Analysis will be provided regarding the gain in IS performance.

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A NON-UNIFORM ADAPTIVE MODEL ORDER REDUCTION TECHNIQUE FOR MODELING COMPOSITE MATERIALS

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ABSTRACT

Computational modeling of composite materials under these extreme conditions, to achieve predictive analysis and design, is an important but challenging task. The challenges particularly come from capturing highly nonlinear behaviors at the microstructural scale and efficiently upscaling from material microstructures to structural components. Among the existing modeling techniques, reduced order modeling (ROM) has gained significant attention due to its ability to balance computational cost and efficiency. The eigendeformation-based reduced-order homogenization model (EHM) has proven to be effective in capturing inelastic responses of complex microstructures, which approximates the microscale problem with a much-reduced basis spanning over partitioned subdomains of the microstructures, where the response of each subdomain is assumed to be uniform. While EHM delivers a hierarchy of gradually refining ROMs ranging from low-fidelity-high-efficiency to high-fiddley-low-efficiency by increasing the number of subdomains (i.e., order of the ROM) used to partition the microstructure, a fixed partitioning of the microstructure is still challenging when involving highly complex geometries and nonlinear behaviors. Efforts have been made to enhance the efficiency of EHM through a Uniform Adaptive Reduced Order Modeling (UAROM) approach, where the simulation switches between a series of pre-defined gradually and uniformly refining ROMS, as the loading and the localization in subdomains continues. However, the ROM order increases substantially and it becomes hard to control since refining happens in all subdomains uniformly. This limitation restricts the flexibility of the method, hindering its applications in modeling highly complex damage initiation and propagation where adaptability and fine control are essential. To tackle these challenges, we propose the Non-uniform Adaptive Reduced Order Model (NUAROM), which draws inspiration from Adaptive Finite Element Methods (AFEMs). In contrast to the uniform approach, the NUAROM only selectively refines the subdomains that have localization reached a certain criterion, similar to the concept of mesh refining around propagating crack tip in AFEM. The applicability and accuracy of NUAROM are verified through numerical examples involving single or multiple inclusion particulate composite microstructures with phase continuum damage and/or cohesive interface damage.

ALGORITHMIC ENCODING OF ADAPTIVE RESPONSES IN TEMPERATURE-SENSING MULTI-MATERIAL ARCHITECTURES

Xiaojia Shelly Zhang[1], Weichen Li[1], Yue Wang[2] and Tian Chen[2]*

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ABSTRACT

We envision programmable matters that can alter their physical properties in desirable manners based on user input or autonomous sensing. This vision motivates the pursuit of mechanical metamaterials that interact with the environment in a programmable fashion. However, this has not been systematically achieved for soft metamaterials due to the highly nonlinear deformation and underdevelopment of rational design strategies. Here, we use computational morphogenesis and multi-material polymer 3D printing to systematically create soft metamaterials with arbitrarily programmable temperature-switchable nonlinear mechanical responses under large deformations. This is made possible by harnessing the distinct glass transition temperatures of different polymers, which, when optimally synthesized, produce local and giant stiffness changes in a controllable manner. Featuring complex geometries, the generated structures and metamaterials exhibit fundamentally different yet programmable nonlinear force-displacement relations and deformation patterns as temperature varies. The rational design and fabrication establish an objective-oriented synthesis of metamaterials with freely tunable thermally adaptive behaviors. This imbues structures and materials with environment-aware intelligence.

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HEALING PERFORMANCE OF ENCAPSULATED FUNGI-BASED SELF-HEALING CONCRETE

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ABSTRACT

This study aims to investigate the development of highly efficient self-healing concrete using fungi. A filamentous fungus strain, Fusarium oxysporum, was chosen, and the study revealed its capacity to germinate and cultivate mycelium within a concrete environment. The alkaline nature of concrete, however, exhibited a decelerating effect on the growth of Fusarium oxysporum. To address this, an innovative approach was explored to establish efficient self-healing concrete by employing a calcium-alginate-based encapsulation technology. Fungi-containing capsules were incorporated into mortar samples at mass ratios of 2%, 3.5%, and 5% to the cement content. The efficacy of this encapsulated fungi-based technology in healing cracks of various sizes in concrete was assessed. Fourier-transform infrared (FTIR) results demonstrated that cracks narrower than 0.1 mm in control samples experienced autogenous healing, while samples containing fungal capsules exhibited a dual healing process involving both autogenous and fungi-based mechanisms. Notably, medium-sized cracks (ranging from 0.1 mm to 0.4 mm) in mortar samples containing fungal capsules achieved complete healing within a 14-day period. The introduction of varying proportions of fungal capsules into mortar samples yielded an impressive repair rate ranging from 73.4% to 94.3% for cracks wider than 0.4 mm, a challenge for conventional self-healing methods.The augmentation of fungal capsule content led to substantial improvements in healing wider cracks. In samples containing 2%, 3.5%, and 5% capsules, healing rates escalated by 464%, 554%, and 597%, respectively, compared to the modest 15.8% rate in control samples. Additionally, the hydrophobic fungal mycelium covering both crack and mortar surfaces significantly curtailed water infiltration, providing an additional advantage by reducing water infiltration and prolonging the durability of structures.

Resilience of coastal structures, systems, and community subjected to hazards
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

RISK ASSESSMENT OF SEAWALL OVERTOPPING CONSIDERING UNCERTAINTIES UNDER CLIMATE CHANGE

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ABSTRACT

This study aims to enhance the protection of coastal communities by better assessing future uncertainties in predicting the risk of failure in coastal defense structures. Sea Level Rise (SLR) poses significant risks to coastal areas, particularly during hurricanes characterized by strong winds and waves. Seawalls, serving as the primary defense, are designed to safeguard seashore infrastructure. However, climate change impacts necessitate reassessing seawall risks, considering potential changes in coastal forces since their initial design. The potential seawall failure, particularly through wave overtopping, poses a serious threat, potentially causing catastrophic flooding in coastal communities. To better understand and characterize the long-term reliability of coastal defense structures amid future uncertainties from SLR and extreme climatic events, a rigorous time-variant reliability framework is proposed for quantifying the risk of overtopping discharge. The carrying capacity in the limit state function is derived from established standards. The overtopping load is determined through prediction with challenges on numerous uncertainties. The proposed probabilistic framework for assessing the risk of overtopping consists of two key components. Firstly, it considers the probability of overtopping discharge based on a specific SLR at seawalls. Secondly, it examines the probability of a specific SLR at seawalls, taking into account various factors such as offshore and nearshore weather conditions, topology, mean SLR change, and more. The factors influencing SLR are categorized into seashore conditions (mean water level at seawall, local weather conditions) and offshore conditions (surges, topology). Predicting SLR at seawalls involves simulating wave propagation from offshore to nearshore, achieved by capturing the relationship between different sensors in these areas. Offshore sensors play a crucial role in recording swell waves that propagate towards nearshore. Additionally, they capture offshore wind conditions, aiding in mitigating the impact of offshore wind on waves. On the other hand, nearshore sensors focus on collecting local wind data. Combining the effects of local wind and waves from offshore provides a comprehensive understanding of the SLR at seawalls. To validate the prediction model, the study compares the predictions of SLR with data obtained from sensors. Ultimately, given a specific SLR at seawalls, the probability of overtopping is determined based on factors such as seawall geometry, local weather conditions, wave speed, etc. The Galveston Seawall on Texas coast is used as a case study. The proposed model functions as a risk-based predictive tool, playing a crucial role in facilitating informed decision-making processes related to coastal infrastructure management and mitigation strategies.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Advances in computer vision, deep learning and artificial intelligence for structural health monitoring and inspections
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AI-ENHANCED ESTIMATION OF POST-DISASTER DEBRIS USING AERIAL IMAGERY

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ABSTRACT

Seeking to enhance the efficiency of post-disaster recovery, this study focuses on utilizing artificial intelligence (AI) and unmanned aerial vehicles (UAVs) for the estimation of debris volume and composition in residential structures. This approach, informed by AI-based damage assessment considering building characteristics, design, and construction methods, aims to address the challenges posed by natural hazards which generate significant debris. These challenges include the expensive and challenging task of debris removal, which forms a considerable part of government budgets for hazard mitigation. Erroneous debris estimation and delayed clean-up operations can endanger public health, obstruct post-disaster search-and-rescue (SAR), and hinder resource distribution efforts by impeding access to affected areas. Traditional methods for disaster debris estimation are often imprecise, with errors as large as 50%. This research, incorporating scaled experiments and analysis of recent hurricane damage footage, indicates that the proposed AI-based approach can be promising in predicting the volume and composition of disaster debris. This finding is expected to provide timely critical insights for emergency response and recovery planning, and for making informed decisions that could reduce the overall debris burden.

Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Probabilistic assessment, data-driven inference and optimization for decision-making under uncertainty
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

GRAPH NEURAL NETWORKS FOR POWER GRID RISK MANAGEMENT

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ABSTRACT

The increasing adoption of renewable energy resources (RES) in power grids, and additional technologies such as bulk storage, gas turbine and flexible plugin devices brings significant uncertainty to power grid management. Hence it is of great significance to assess the risk associated with a power dispatch decision to promote operators' situational awareness. Quantifying the operational risk under uncertainty requires to solve large number of optimal power flow (OPF) analyses and generator commitment (referred to as security-constrained unit commitment, SCUC) problems to cover a wide range of probabilistic forecasts of load demand and RES power supply. However, it is computationally prohibitive to solve numerous OPF and SCUC problems (both of which are optimization problems) within the decision window using numerical solvers, especially for large power grids. Therefore, it is necessary to develop efficient surrogate models that can solve OPF and SCUC problems quickly and accurately to deal with the frequent variation of grid variables.

In this work, graph neural network (GNN)-based surrogate models are developed to facilitate OPF and SCUC computation. The fundamental idea of GNN is to consider grid variables at each node as a feature vector and recursively update its representation according to neighborhood information. GNN takes the advantage of grid network topology in the calculation process and thus promotes the computational efficiency significantly. A well trained GNN model can provide quick and accurate OPF and SCUC predictions for various load demand and RES supply scenarios, making it a good choice for real-time operational risk assessment.

GNN surrogate models are trained in this work using supervised learning with numerical solutions as ground truth. The surrogates take load demand and RES power supply as inputs and predict multiple outputs including active power (node-level), transmission line flow (edge-level) and load shedding, operating reserve and total cost (system-level). Given the probabilistic forecasts of demand and supply, GNN surrogates can quickly generate numerous Monte Carlo (MC) samples which are then used for risk quantification. Versatile tools are developed to allow model evaluation and network risk assessment, and model generalization capacity is also investigated using statistical metrics. It is shown that the GNN surrogates are sufficiently accurate for predicting the grid state and enable fast as well as accurate operational risk quantification and risk management decision-making. The GNN approach can also be generalized for other infrastructure systems with network structure.

LSTM FOR METAMODELING OF HIGH-DIMENSIONAL STOCHASTIC SYSTEMS AND ITS APPLICATION TO ACTIVE LEARNING-BASED RELIABILITY ANALYSIS

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ABSTRACT

Metamodeling techniques have received increasing popularity in recent years since they can replace the original time-consuming physical model and remarkably reduce the computational burden. Commonly used surrogate models such as polynomial chaos expansion and Gaussian process regression are widely used and show their feasibility and superiority in the field of uncertainty propagation. However, they can hardly be applied to the high-dimensional stochastic dynamic systems since a large number of random variables are required to simulate the stochastic excitation. To tackle this issue, a powerful machine learning tool termed the long short-term memory (LSTM) is employed to deal with the stochastic excitations. LSTM can well capture the time-dependent property of the sequency-to-sequency data, which can be employed to predict the structural time history responses and circumvent the high-dimensional random phases for generating the stochastic excitation. Besides, to consider the uncertainties of structures, the structural random variables are embedded into the LSTM network. Moreover, to address the insufficient efficiency of neural network for uncertainty propagation results from the limited observations, the active learning strategy is combined with the LSTM to improve the accuracy of reliability analysis, which makes the active learning available for the high-dimensional stochastic dynamic systems.

HOT DEFORMATION OF METALLIC HONEYCOMBS: MECHANISMS AND MODELLING

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ABSTRACT

Architected cellular materials exhibit exceptional mechanical properties, such as ultralight, ultrastiff, and even respond to external stimuli through tailoring geometry and topology rather than changing composition. Such materials have the potential to be applied in extraterrestrial construction and expeditionary efforts, which usually require them to perform under high-temperature environments. Despite this, limited research investigated the performance of architected cellular materials under high temperatures. Addressing this gap, our study utilizes recent advances in additive manufacturing to create a series of heat-resistant alloy honeycomb structures using ABD-900AM. This research focuses on the processing, characterization, and analysis of the deformation behavior of these metallic honeycomb structures at both room temperature and 900°C. Through a combination of experiments and simulations, we have gained a comprehensive understanding of the deformation mechanisms and their interaction with damage pathways across various temperatures. Additionally, we explored the effects of oxidation and the intrinsic ductility of the material.

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

OPERATORS LEARNING FOR MULTISCALE MODELING: AN EXAMPLE OF ELASTIC-VISCOPLASTIC STRUCTURAL MATERIAL

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ABSTRACT

Multiscale systems, due to its complexity in mechanisms, attract significant attention, such as the work on statistical and model errors [1]. Many machine learning frameworks have been developed to obtain surrogate models to reduce the computational complexity of such multiscale systems. One of the fundamental challenges is the dependence of machine-learned models on the discretization of input data matching that of the training data. In solid mechanics, the mapping from the function space of deformation gradient to the function space of Cauchy stress is an operator which should be discretization-invariant. Here, our principal contribution is that we apply the recurrent neural operator (RNO) framework to learn the solution operator between the homogenized strain and the homogenized stress for a material at microscale. The RNO is an architecture of deep neural networks that can give insight into the physics of the macroscopic problem, such as the number of internal variables [2]. As an example, we consider a two-dimensional truss structure, where each truss is elastic viscoplastic. RNOs are learned from the deformation gradient to the homogenized Cauchy stress of the microscale model. We will talk about the discretization invariant property of the RNOs and the insight obtained from the internal variables theory of the microscale model. Then we apply the RNOs to multiple macroscale problems subject to various boundary conditions. Further improvement of the RNOs for macroscale models and relevant uncertainty will be explored and discussed [3].

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ACOUSTIC EMISSION MONITORING AND DIAGNOSIS OF INTERFACIAL BOND-SLIP DAMAGE OF CFST COLUMNS

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ABSTRACT

CFST structures are composed of steel tubes filled with concrete, and they have strong load-bearing capacity and excellent seismic performance. The use of CFST structures in large-span arch bridges can effectively reduce the self-weight of the structure and improve the overall stability of the bridge. However, the bonding performance between the steel tube and the core concrete has a significant impact on the overall load-carrying capacity of CFST structures. In order to study the damage law of the interface between concrete and steel tube in CFST columns, we propose a real-time monitoring and evaluation method for interface damage of CFST columns based on acoustic emission technology. Push-out experiments of CFST column interfaces were conducted to collect acoustic emission signals of interface damage. Through the analysis of acoustic emission characteristic parameters, RA-AF correlation analysis, and b-value analysis, the identification of damage stages, analysis of crack propagation, and evaluation of damage severity of the interface bonding failure process can be achieved. Based on acoustic emission hit rate, cumulative ring count, and cumulative energy features, the damage process of CFST column interfaces can be accurately divided into elastic stage, slip expansion stage, and complete slip stage. Through RA-AF correlation analysis, the crack development pattern of CFST column interfaces is revealed. The b-value analysis effectively reflects the severity of damage in CFST interfaces. The research findings above can provide a foundation for the application of acoustic emission technology in practical CFST arch bridge engineering and theoretical support for the full-life safety monitoring and operational maintenance of CFST arch bridges.

Keyword: CFST, Acoustic emission, Interface failure, Push-out test, Damage monitoring

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

INVESTIGATING BENDING, RADIAL, AXIAL, AND TORSIONAL MECHANICAL BEHAVIOR OF A NOVEL TUBULAR METAMATERIALS

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ABSTRACT

Strengthened tubular structures have had a significant impact on various industries. Advancements in aircraft, construction, medical implants, robotics, and renewable energy have improved safety, efficiency, and durability in multiple sectors. This section explores the practical applications of medical health, using Nasal Swabs as an example, under different loading scenarios. Oue designed tubular strecutures provides a promising perspective on enhancing the mechanical performance of tubular structures. To evaluate the mechanical advantages of the bioinspired design approach, we conducted 3-point bending, radial, and axial compression tests on 3D printed tubular lattice structures. The tests showed that the tubular structure displayed improved bending properties and was approximately twice as stiff as traditional tubular designs. Furthermore, the sponge-inspired design exhibits significantly higher strength and toughness compared to traditional designs, with approximate improvements of 3 and 4 times, respectively. Numerical simulations revealed that these enhancements are attributed to the strengthening effect of struts, which distribute stress evenly and allow for bending without excessive stress concentration. The design shows improved resistance to radial and axial loading, with approximately 1.3/3 times greater radial/axial compression stiffness compared to unreinforced designs. These improved mechanical properties of tubular metamaterials make them suitable for a wide range of applications.

Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DIGITAL TWINNED CYBER-PHYSICAL SYSTEM FOR UNDERSTANDING INFRASTRUCTURE OPERATIONAL STATE

Zhidong Zhang[1], Zahra Zhiyanpour[1], Mehrdad Shafiei Dizaji[2], Ayatollah Yehia[1] and Devin Harris[1]*

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[2]Federal Highway Administration

ABSTRACT

The primary aim of this research is to introduce a digital twin-enabled cyber-physical system designed to comprehend the operational state of infrastructure systems. This system integrates AI-driven simulation and experimentation within a real-time collaborative environment, enhancing the understanding of an infrastructure system's current operational state. This approach proves more adept at sensing, analysis, and diagnosis. Accurately and efficiently assessing infrastructure system operational state, such as determining the safety level of aging bridge components or evaluating the energy dissipation capacity of fuse components within a lateral force resisting system after seismic events, is pivotal for informed decision-making processes. To materialize this digital twin-enabled cyber-physical system, AI-powered simulation models, validated against Finite Element Modeling (FEM), and AI-driven image-based experimental measurement models using Digital Image Correlation (DIC) are leveraged for real-time estimations. This study introduces a Mixed Reality (MR) environment, enabling users to interact by selecting baseline AI simulations (e.g., structural members with idealized boundary conditions) and adjusting model parameters (e.g., boundary conditions, constitutive properties) or identifying uncertain features (e.g., damage locations) based on image-derived observations. Validating the proposed Digital Twin prototype involves employing full-scale beam experiments and simulations to assess real-time accuracy, reliability, and computational expenses. Overall, this research establishes communication protocols between AI-driven simulation and AI-powered experimentation and resolves real-time data processing that allows for user engagement and exploration across visualization platforms. The digital twin-enabled cyber-physical system can be extrapolated to larger-scale infrastructure, enhancing efficient human decision-making, and contributing to the evolution of structural health monitoring.

Recent advances in sensing, SHM, and automated inspections for infrastructure condition assessment: Toward actionable solutions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMAGE-BASED REAL-TIME BEHAVIOR MEASUREMENT OF PHYSICAL INFRASTRUCTURE SYSTEMS DRIVEN BY DEEP LEARNING

Zhidong Zhang[1], Ayatollah Yehia[1], Zahra Zhiyanpour[1], Mehrdad Shafiei Dizaji[2] and Devin Harris[1]*

[1]*University of Virginia*
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ABSTRACT

This research aims to introduce an AI-enabled real-time measurement protocol for assessing complex behaviors within physical infrastructure systems, employing the Digital Image Correlation (DIC) technique. The efficient and accurate evaluation of the operational state of infrastructure systems, such as determining the safety level of bridges in service or evaluating the energy dissipation capacity of lateral force resisting systems after seismic events, is pivotal for human decision-making processes. While DIC has revolutionized full-field measurements and non-destructive assessments, its data-intensive nature and requirement of complex equation solution have limited real-time applications. This study proposes to employ AI-driven approaches to formulate real-time measurements of physical infrastructure systems and enable user-guided inquiries of behavior during experiments, thus further enhancing analysis and diagnosis capabilities. To realize AI-driven real-time measurements, a deep Convolutional Neural Network (CNN) is developed to learn correlations between sequences of DIC speckle pattern images and their corresponding deformation fields. The proposed CNN will be first developed for 2D speckle patterns and the corresponding in-plane deformation field and then extended to 3D. Utilizing both artificially curated speckle pattern image pairs with pre-defined deformation patterns and real-world speckle datasets taken from past experiments, the CNN model is trained. The CNN model will be tested on experimental data collected from full-scale structural response experiments subjected to diverse loading and boundary constraints, unseen during training. The research herein can be further incorporated into a digital twin-enabled cyber-physical system. The implications extend to larger-scale infrastructure, augmenting human decision-making efficacy, and advancing structural health monitoring practices.

Data-driven methods and research for physical testing in structural engineering
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DATA-DRIVEN PREDICTION MODELS FOR THE BACKBONE CURVE OF COLD-FORMED STEEL FASTENER CONNECTIONS

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ABSTRACT

The main objective of this study is to present the recently assembled cold-formed steel (CFS) fastener connection test database, and to investigate the application of machine learning models on fastener connection backbone prediction. Predicting the behavior and performance of fastener connections, as significant nonlinearity may arise from materials, contact, and connected structural members. Therefore, experimental testing plays a dominant role in studying the behavior of CFS connections, as well as providing valuable data covering strength, drift, and hysteretic behaviors. A large data set for CFS fastener connection load-deformation response was initiated, which currently holds 550 monotonic and cyclic load-deformation response curves from tests on screw-fastened and power-actuated fastened ply-to-ply connections. On top of the design provisions for CFS fastener connections derived from testing data, data-driven predictions, from various machine learning algorithms, may provide reliable, widely applicable, and efficient predictions on the strength or even the full backbone curve of fastener connections. The research herein employs a series of machine learning models including Support vector machines (SVMs), Artificial Neural Network (ANN), Random Forest (RF), and eXtreme Gradient Boosting (XGBoost) are constructed and trained to provide backbone prediction for CFS fastener connections. The performance of various machine learning algorithms is compared and discussed. Features impacting the connection strength mostly are provided by the algorithms and further discussed. This research can make high-quality data-driven models and corresponding CFS connection physical test data easily accessible, and the data-can advance state-of-art CFS connection design and research.

ROLE OF INSURANCE CLAIMS DATA FROM HURRICANES IN CATASTROPHE MODELING

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ABSTRACT

Catastrophe models are an integral part of the insurance value chain and help transfer the risk between homeowners, (re)insurers and capital markets. Calibration and validation of models therefore becomes extremely crucial in obtaining reliable and robust risk estimates. Numerous studies exist in the risk and actuarial space that demonstrate various utilities of insurance claims data in the insurance value chain. These include use of claims data to inform underwriting decision, owning the view of insurer's risk in terms of adjusting, calibrating and validating catastrophe modeling outputs.

This study presents two novel applications of insurance claims data towards building catastrophe models with focus on hurricanes. The first study looks at identifying damage patterns among residential claims specific to hurricanes. Post-hurricane damage surveys have shown that buildings with specific characteristics exhibit different damage patterns. This study analyzes the claims data collected in the aftermath of 2017 Hurricane Irma as a case study. The Density-Based Spatial Clustering of Applications with Noise (DBSCAN) method is used for geospatial data clustering and outlier analysis. With the DBSCAN method, clusters and outliers of damaged versus intact buildings are detected. The clusters help locate strong and weak neighborhoods during the hurricane and analyze the influential factors. Results show that the replacement value of residential homes is an important factor in damage formulation. A clear separation was observed between homes with a replacement value threshold of about100,000 USD, which cannot be clearly detected in the raw data without clustering and outlier analysis.

The second study explores the use of claims data to understand relative vulnerability as a function of wind speed between buildings used for various functional purposes, referred to as occupancy. Vulnerability functions, also referred to as damage functions are frequently used in catastrophe models and help derive estimates of damage ratio (ratio of loss to the replacement value) as a function of intensity. The relativities between occupancy classes are developed using a multi-task learning (MTL) method. The MTL method allows fitting damage function curves for multiple occupancy classes in parallel. It considers the commonality between fitting tasks and improves the generalization of fitted models with less overfitting. Moreover, through implementation using a neural network model, the MTL method provides an approach for synergistically combining the claims data and engineering knowledge in the damage function development.

DYNAMIC RUPTURE MODELING IN A COMPLEX FAULT ZONE WITH DISTRIBUTED AND LOCALIZED DAMAGE

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ABSTRACT

Earthquakes are among the most destructive natural hazards in our planet. They also present a unique opportunity to study dynamic fracture at scale, but their underlying physics remain far from being fully understood. While at some level, earthquakes exemplify quasi-brittle fractures occurring along frictional fault interfaces, these events can also dynamically trigger co-seismic off-fault damage, manifesting as both distributed and localized effects that influence fault zone geometry and rheology. To accurately quantify the impact of dynamic ruptures on the bulk materials within the damage zone, it is essential to employ numerical models capable of capturing the evolving material properties guided by field observations.

Here, we implement a continuum damage breakage (CDB) rheology model in our MOOSE-FARMS dynamic rupture simulator to investigate the interplay between bulk damage and fault motion on the evolution of dynamic rupture, energy partitioning, and ground motion characteristics.

The CDB rheology model combines aspects of a continuum viscoelastic damage framework for brittle solids with a continuum breakage mechanics for granular flow within dynamically generated slip zones. It consists of a scalar damage parameter to account for the density of distributed cracking, along with a breakage parameter to represent grain size distribution of a granular phase. The model can capture both the degradation in the elastic properties and the brittle instabilities which further promote post-peak rheological softening and transition into granular flow. MOOSE-FARMS is an in-house application developed based on MOOSE framework to simulate dynamic rupture using cohesive zone model. It accepts various frictional laws, fault geometries, and bulk rheologies.

We demonstrate several effects of damage and breakage on rupture dynamics in the context of two prototype problems addressed currently in the 2D plane strain setting: (1) a single planar fault and (2) a fracture network. We quantify the spatial-temporal reduction in wave speeds associated with dynamic ruptures in each of these cases and track the evolution of the original fault zone geometry. The results highlight the growth and coalescence of localization bands as well as competition between localized slip on the pre-existing faults vs. inelastic deformation in the bulk. We analyze difference between off-fault dissipation through damage-breakage vs. plasticity and show that damage-induced softening increases the slip and slip rate, suggesting enhanced energy radiation and reduced energy dissipation. We discuss the implications of these results on our understanding of earthquake source and fault physics as well as near-fault seismic hazard.

Design and additive manufacturing of engineering structures and materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AUTOMATED DESIGN-ANALYSIS-OPTIMIZATION WORKFLOW FOR AEROSPACE STRUCTURES USING ISOGEOMETRIC KIRCHHOFF–LOVE SHELLS

Han Zhao[1], David Kamensky[1], John Hwang[1] and Jiun-Shyan Chen[1]*

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ABSTRACT

Shell structures, known for their exceptional stiffness and strength-to-self-weight ratios, play an important role in aircraft design. The geometric properties of these structures have significant impacts on their performance, making shape optimization essential for achieving superior designs. In industrial standards, computer-aided design (CAD) models of aerospace structures are represented by a collection of Non-uniform rational B-spline (NURBS) surfaces. In this work, a FEniCS-based Python framework using isogeometric Kirchhoff–Love shell model [1] is presented to enable direct structural analysis for CAD models, entirely bypassing the process of finite element (FE) mesh generation. To ensure displacement and rotational continuity at NURBS surface intersections, a penalty-based coupling formulation is implemented [2]. The unified description between CAD and analysis models in isogeometric analysis (IGA) provides a unique advantage in shape optimization, where the control points of the CAD model served as design variables are updated directly during optimization. Therefore, the same NURBS basis functions can be employed to represent the updated geometry for analysis in subsequent optimization iterations, making the associated CAD model directly applicable in manufacturing. In the optimization process, the free-form deformation (FFD) technique is employed to perform shape optimization of aerospace structures while preserving connectivity at surface intersections [3]. The CAD geometry is embedded in a trivariate B-spline block, whose shape is updated through control point adjustments of the B-spline block. Furthermore, a novel scheme is proposed for shape optimization with differentiable surface intersections, allowing for the movement of shell intersection locations without compromising the mesh quality of NURBS surfaces. We apply this methodology to optimize the layout of internal stiffeners in an aircraft wing to demonstrate its benefits in real-world aerospace design scenarios.

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Advances in regional hazard modeling and risk assessment
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING THE EFFICIENCY OF EARTHQUAKE RUPTURE FORECASTING MODELS WITH ADAPTIVE IMPORTANCE SAMPLING IN REGIONAL SEISMIC RISK ASSESSMENT

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ABSTRACT

In regional probabilistic seismic risk analysis (PSRA), the uncertainty of earthquake rupture (e.g., magnitude, epicenter, etc.) and aleatory ground motion uncertainty must be considered. Such uncertainty is conventionally propagated to civil infrastructure responses using a two-step Monte Carlo (MC) method. In the first step, the uncertainty in the earthquake rupture scenario is considered, and a number of earthquake scenario samples are generated. In the second step, a mean field of ground motion intensity measures is estimated for each scenario using ground motion prediction equations (GMPEs), and inter-event/intra-event residual samples are added to the mean field to create a number of ground motion field (GMF) samples. The GMF samples are then used as the input to determine civil infrastructure performance. The first MC step is usually called earthquake rupture forecast (ERF) and requires expertise in seismology. As a result, earthquake engineers usually take the scenario samples created by developed ERF models and create GMF samples for the sample scenarios.

Because a number of GMFs are sampled for each ERF scenario, the number of GMF samples can be huge (almost 700,000 in the PSRA of a region in New Zealand [1]). The importance sampling (IS) method has been proposed to apply in both MC steps to reduce the number of GMF samples [2]. However, the IS method is difficult for practitioners to apply because it is not implemented in the preestablished ERF models. As a result, this research proposes a workflow to reconstruct a set of IS samples from the uniform MC samples produced by ERF models. A sampling-based adaptive algorithm is introduced to estimate the optimal proposal IS densities across conflicting outputs, and a PCA-based formulation is applied to handle the high-dimensionality of outputs. The algorithms will be demonstrated with a PSRA of a transportation system. The proposed method is expected to produce smaller estimation variances than existing IS algorithms because an optimal proposal density is selected. The proposed method is also unbiased, which is a property that the optimization-based down-sampling algorithms don’t preserve and is easier to apply by earthquake engineers.

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TOWARDS A COMPUTATIONAL PLATFORM FOR INTEGRATED REGIONAL RESILIENCE ASSESSMENT OF INTERDEPENDENT SYSTEMS

Nikola Blagojevic[1], Jinyan Zhao[2], Sina Naeimi Dafchahi[2], Adam Zsarnoczay[3], Frank McKenna[2], Matthew DeJong[2] and Bozidar Stojadinovic[1]*

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ABSTRACT

Compared to the existing regional risk assessment tools, regional resilience assessment tools need to consider the post-disaster recovery of the built environment, thus estimating its ability to bounce back following a disaster. Furthermore, the built environment needs to be viewed as a system-of-interdependent-systems, instead of an aggregate of individual assets. To that end, the SimCenter's R2D Tool is integrated with the pyrecodes open-source software for regional resilience assessment to extend the R2D Tool's risk-assessment capabilities beyond direct losses by simulating the post-disaster regional recovery of interdependent systems, thus capturing indirect losses, such as system downtime, population displacement and business interruption. Recovery simulation of an individual system in pyrecodes requires two modeling elements: one to simulate the recovery of systems' components and the second one to simulate the flow of resources among components. Recovery is simulated as a time-stepping loop where at each time step the functionality of components is updated, conditioned on the available recovery resources and the progress in component's impeding factors and repair. The simulated flow of resources among components captures interdependencies: at each time step of the recovery simulation, each component's ability to supply resources to other components is conditioned on the component's resource demand fulfilment, assessed using resource flow models. The recovery and resource flow simulation of individual systems can be performed using the algorithms in pyrecodes or using third-party simulators which connect to pyrecodes using standardized application programming interfaces (APIs). The integrated regional resilience assessment of interdependent systems is demonstrated by assessing seismic resilience of the city of Alameda, CA, considering three interdependent systems: the building stock, the transportation network and the water supply network. Two infrastructure systems simulators are integrated within the R2D Tool and pyrecodes workflow using different integration modalities. The traffic flow is simulated using the spatial queue model and the recovery of the transportation system is simulated using pyrecodes' built-in algorithm, while both the recovery and resource flow of the water supply system are simulated using the REWET software. The recovery of the building stock and the flow of resources provided by the building stock are simulated using pyrecodes' algorithms.

RESEARCH ON THE DEFORMATION AND DAMAGE PROCESS OF CRUSHED-ROCK HIGHWAY EMBANKMENT IN PERMAFROST AREAS

Runmin Zhao[1], Xiaoming Huang[1] and Tao Ma[1]*

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ABSTRACT

Most current research on crushed-rock interlayers for highway embankments in permafrost regions primarily focuses on thermal properties, with limited exploration of their mechanical deformation characteristics. To address this gap, this study investigates the deformation and failure processes of crushed-rock interlayers under long-term settlement deformation of permafrost foundations. The study employs a coupled Finite Element Model (FEM) and Discrete Element Model (DEM) to comprehensively consider the discrete characteristics of the crushed-rock interlayer.

In contrast to previous DEM-FEM coupling methods, this study introduces a static FEM coupled with an explicit DEM process to simulate the long-term settlement deformation of crushed-rock interlayer highway embankments and permafrost foundations over a 20-year period. The coupling algorithm involves calculating temperature fields and long-term freezing and thawing foundation deformation in the FEM model, with the thermal control equations developed by our research group [1] and the E-P constitutive model developed by Zhang et al. [2]. Deformation calculations for the crushed-rock interlayer are carried out in the DEM model. The interaction between FEM and DEM is facilitated through force and coordinate data transfer using Python-coded scripts and a Fortran-coded DLOAD subroutine. Notably, relative velocities at the contact points between DEM and FEM are ignored due to the slow speed of the long-term deformation.

The results indicate that for the granite blocks employed in the Gonghe-Yushu expressway, the blocks are seldom broken. Instead, the deformation of the crushed-rock interlayer primarily results from the relative movement and rearrangement of the blocks. It is recommended to adopt a large-porosity randomly piled crushed-rock interlayer composed of blocks with sharp corners. When the size of block varies from 20cm to 40cm, the block size has no obvious effect on the deformation of crushed-rock interlayer, therefore the block size could be determined only by the cooling effect. At the meantime, the structure layer above the crushed-rock interlayer should also be rigid enough to ensure a smaller uneven settlement value for the superstructure.

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Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LUNAR HABITAT ARCH-SHIELD OPTIMIZATION FOR COMPLEX LOAD COMBINATIONS WITH ML

Yang Zhao[1] and Christian Malaga-Chuquitaype[1]*

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ABSTRACT

The scientific curiosity and passion for space exploration, driven by technological advancements and increased computational power, have been rekindled at academic institutions and private companies. Constructing a permanent human habitat on the Moon is generally regarded as the next challenge and an outpost of further exploration missions to other celestial bodies. The concept of using inflatable structures with a regolith 3D-printed shield is getting momentum in tandem with advancements in additive manufacturing technologies. This paper focuses on the search for an optimal arch shape of such regolith-based structures by addressing the challenges caused by multiple load combinations, including gravitational, thermal, and seismic loads. This process can be viewed as an optimization of a high-dimensional data space, and autoencoders, a type of unsupervised machine learning, can be leveraged to explore it. These models compress data into a reduced latent space and reconstruct the original data from these reduced dimensions, which means once optimal latent space variables are identified, the models can reconstruct the desired output shapes. To ensure the reliability of the model, the generation of training data sets and the choice of optimization methods are crucial. For data set construction, a random sampling method is employed to maximize coverage, and then corresponding contoured datasets reflecting maxima of stress and displacement responses are generated by means of algorithms running Abaqus models. For the optimizing procedure, Bayesian Optimization is applied to conduct multi-objective optimization. The optimal shapes obtained in this study are compared with previous proposals and the differences are highlighted. This study provides a valuable reference for future regolith-based shape design.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

REINFORCEMENT LEARNING-POWERED MODEL-FREE FRAMEWORK FOR UAS-BASED BRIDGE COLUMN INSPECTION MISSION PLANNING

Yuxiang Zhao[1] and Mohamad Alipour[1]*

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ABSTRACT

The application of Unmanned Aerial Systems (UAS) in bridge inspection has been extensively discussed. Various studies have investigated mission planning methods for efficient and reliable bridge inspection, while most of them rely on a CAD model or preliminary scanning data as inputs, which are not often available in practical scenarios. This work aims to achieve higher-level automated inspection by introducing a reinforcement learning based, model-free mission planning framework specifically for inspecting bridge columns, eliminating the need for input data. A parametric environment generator was employed to create diverse bridge column plans, which is the basis for training the agent. As the core of this mission planning approach, a deep neural network served as the agent. It iteratively processed the environment map and position inputs and generated decisions regarding movement or scanning to formulate an optimal inspection plan. During agent training, the efficiency of the mission plan was evaluated as a reward, constrained by inspection quality. The techniques for obtaining observations were also discussed for future real-world application. The proposed framework demonstrated the feasibility of utilizing reinforcement learning in on-line mission planning for bridge column inspection, significantly enhancing the automation and performance of bridge inspection procedures.

Architected materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTIPHYSICS TOPOLOGY OPTIMIZATION OF ARCHITECTED MAGNETIC SOFT MATERIALS WITH CONTINUOUS MAGNETIZATION ORIENTATIONS

Zhi Zhao[1], Chao Wang[1] and Xiaojia Shelly Zhang[1]*

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ABSTRACT

In recent years, magnetic-responsive soft architected materials have garnered attention for their wireless and rapid actuation capabilities under magnetic fields, enabling versatile applications in robotics, biomedicine, and vibration mitigation. This study specifically focuses on hard-magnetic soft materials made by embedding high-coercivity magnetic particles, such as neodymium–iron–boron alloy, within a soft matrix, providing remarkable programmability and various functionalities. From a design perspective, many current designs for the architected magnetic material exhibit discrete magnetization orientations, potentially limiting actuation performance and posing fabrication challenges at magnetization transition points. This work introduces a novel multiphysics topology optimization framework that simultaneously optimizes geometry and ensures continuous remnant magnetization distributions in the architected magnetic material. The optimized continuous magnetization offers several demonstrated advantages: 1) Enhanced actuation performance through an expanded design space with arbitrary magnetization orientations; 2) Mitigation of undesirable sharp changes in magnetization, reducing repelling forces and improving fabricatability; 3) Feasibility of fabricating designs with continuous magnetization using the recently developed magnetic direct-ink-writing technique. Our developed design approach has successfully achieved programmable shape transformations, multi-functional actuators, and magnetic metamaterial with tunable lateral deformation. This innovative approach explicitly explores the potential of architected materials in the context of hard-magnetic soft materials, emphasizing improved enhanced performance and the alleviation of abrupt changes in magnetization orientation.

Topology optimization: From algorithmic developments to applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

TOPOLOGY OPTIMIZATION OF STRUCTURES WITH NONLINEAR SUPPLEMENTAL DAMPING

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[3]*Universidad de Cuenca*
[4]*Skidmore, Owins & Merrill*

ABSTRACT

Extensive research has been done on structural optimization and optimal placement and designs of dampers separately, but there is limited research about simultaneous optimization of structural and damper designs with nonlinearity. Structures in seismic prone regions are often designed with respect to their element's inelastic behaviors such as the use of nonlinear dampers to reduce the structural response, showing the need to consider nonlinearity in the design process. The purpose of this study is to propose a method to perform simultaneous optimization of topology with supplemental damping devices modeled as nonlinear viscous dampers. One observation is that use of nonlinear dampers has impact in the optimal topology as compared with linear dampers. Nonlinear dampers also tend to decrease the optimal drifts and velocities of the system, meanwhile also increase the amount of energy dissipated by damping in the system as compared with linear dampers. In conclusion, optimization of structures considering nonlinear dampers is more effective in seismic damage mitigations and should be included to ensure an optimal design.

Uncertainty quantification and machine learning for design, optimization, and inference in multiscale systems
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

THE PHYSICS-INFORMED COMPOSITIONAL OPERATOR NETWORK

Weiheng Zhong[1] and Hadi Meidani[1]*

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ABSTRACT

We focus on solving partial differential equations (PDEs) with variable parameters. To this end, neural operators as an effective machine learning method are trained as mapping from these parameters to their corresponding solutions. A significant challenge in training neural operators is the requirement for large datasets of paired input-output examples, which are often expensive and time-consuming to produce. As a solution, neural operators trained through physics-informed methods have gained attention. However, existing physics-informed neural operators struggle with issues such as accommodating irregular domain shapes or generalizing across different dimensions of parameter observations. We propose a novel model architecture that successfully overcomes these hurdles. It is designed to generalize across diverse parameter observation dimensions within irregularly shaped domains. Moreover, this innovative architecture is compatible with physics-informed training, thereby bypassing the need for finite-element methods in creating training data. Our results show that this novel model not only matches but potentially surpasses the performance of traditional data-driven neural operators.

INCORPORATING PCM-ENABLED THERMAL ENERGY STORAGE INTO 3D PRINTABLE CEMENTITIOUS COMPOSITES FOR BUILDING ENERGY SAVING

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[3]*University of Alaska Fairbanks*

ABSTRACT

This resarch delineates the feasibility of incorporating microencapsulated phase change materials (mPCM) into 3D printable cementitious composite materials. A comprehensive experimental program was carried out to evaluate the impacts of mPCM on the printability, microstructures, mechanical and thermal properties of cementitious 3D printing ‘inks’. Results showed that the mPCM affected the printability of the cementitious ink material based on its physical properties (e.g., particle size) and volume loading – at lower volume loadings, mPCM increased the flowability of the cementitious ink material while leading to increased compressive strength and thermal conductivity for the hardened printed material. However, further increase in mPCM dosage led to a decrease in printability and, therefore, decrease in compressive strength and thermal conductivity as compared to the reference mixture. The results also showed that the inclusion of mPCM influence the printing parameters. In general, the inclusion of higher volume contents of mPCM necessitates a higher extrusion rate to achieve a desirable extrudability. Lastly, a thermal network model was formulated for 3D printed mPCM charged building components (e.g., wall). The study shows that microencapsulated PCM materials have good potential to be used in 3D printable cementitious mixtures for improving the thermal and energy performance of 3D printed buildings.

On the mechanics of road and paving materials in the cold, Nordic, and Arctic Regions
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

COAL-DERIVED CONDUCTIVE PAVEMENT FOR WINTER DE-ICING - PROTOTYPE, MODELING, AND SIMULATION

Hongyu Zhou[1], Yawen He[1], Yucen Li[1], Yanhai Wang[1] and Baoshan Huang[1]*

[1]*University of Tennessee*

ABSTRACT

Traditional de-icing methods and heating systems for pavements show limitations in high installation and maintenance costs, traffic delays, excessive weariness, and negative environmental and public safety impacts. In this research, a novel low-cost coal-char bearing multifunctional pavement material was developed and demonstrated for smart self-heating pavements. An innovative pathway to designing and constructing a self-sensing and self-heating pavement system was proposed by incorporating this byproduct of coal pyrolysis as a de-icing system heating layer into the pavement structure. This coal-derived carbon exhibits highly tailorable electrical conductivity, superior cost-efficiency, and wider compatibility for aggregate alternatives as compared to other conductive pavement additives. The coal-char charged asphalt mixture for the self-heating pavement was designed and prototyped. The mechanical, electrical, and thermophysical properties of coal-char bearing pavement materials were characterized through multiscale material tests. A laboratory prototype was produced, and bench-scale slab heating and de-icing experiments were conducted. The test results indicate that the embedded electrically conductive layer made from coal-char asphalt can serve as an effective heating system for de-icing. Additionally, a simulation case study was performed using a thermal network model with experimental calibration to quantify the thermal performance and energy consumption of the de-icing system. A rule-based control strategy is designed for the de-icing system based on heating demands.

Advanced engineering concepts, designs, and technologies for aerospace and extraterrestrial applications
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DETECTION, EFFECTS, AND RETROFITTING OF PRINTING DEFECTS OF 3D PRINTED CONCRETE STRUCTURES

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ABSTRACT

Understanding the effects printing defects have on the mechanical performance of concrete 3D printed structures and developing facile methods for identifying defects and retrofitting structural members is necessary for infrastructure development on the lunar surface and beyond. In this study, various defect sizes, quantifies, and orientations were artificially introduced by placing spherical expanded polystyrene (EPS) foam beads of a known diameter into 3D printed concrete specimens. The effect that the introduced voids had on the mechanical performance was then evaluated by testing cube specimens cut from the printed elements and tested under compression. Methods for identifying both external printing defects on the face of printed elements and internal defects located within printed elements were developed based on computer vision and ultrasonic testing techniques. Next, materials and methods to retrofit the defected specimens were developed. The mechanical properties were characterized to guide the selection of the most effective retrofitting materials. Two materials with the highest capacities in the mechanical properties characterizations were selected. Furthermore, methods for retrofitting printed elements using the materials selected in the previous stage of the project were developed alongside defect detection methods. These methods were then deployed in tandem to retrofit the defected specimens.

FINITE ELEMENT MODELING OF CREEP-INDUCED SUBSIDENCE ALONG COASTAL LOUISIANA WITH GPS MEASUREMENTS

George Z. Voyiadjis[1], Yaneng Zhou[1] and Ahmed Abdalla[1]*

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ABSTRACT

The subsidence rates are generally between 2-7 mm/yr during the last one or two decades based on GPS measurements at continuously operating reference stations along coastal Louisiana. The creep mechanism in Holocene sediments is adopted to quantitatively interpret the observed land subsidence along coastal Louisiana. An extended elasto-viscoplastic model is developed to better consider the viscoplastic deformation for overconsolidated soils with small strain rates. The implemented constitutive model is calibrated and validated in ABAQUS based on both creep and constant rate of strain laboratory experiments for Batiscan clays. Finite element models are then constructed to analyze the creep-induced subsidence for Holocene sediments at several stations along coastal Louisiana. The finite element models are calibrated with GPS-derived subsidence by using the extended elasto-viscoplastic model with typical material parameters for lightly overconsolidated soils. The modeled subsidence decreases significantly with increasing both the initial overconsolidation ratio and the strain-rate exponent, and the subsidence rate decreases with time. Creep-induced subsidence is predicted for several stations based on the calibrated finite element models, and the subsidence is around 30.4 cm in 50 years during 2005-2055 at station GRIS in Grand Isle.

Computational geomechanics
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MULTISCALE MODELLING FRAMEWORK FOR THE MECHANICAL PROPERTIES OF ILLITE

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ABSTRACT

Clay is one the most important materials in earth's crust and has wide applications in geotechnical, environmental, and biomedical engineering. It has complex mechanical properties due to its particulate nature and complex physico-chemical interactions between primary particles. In this presentation, a multiscale framework will be presented, linking the mechanical properties of illite from atomistic up to macroscopic scales. Illite is a typical type of clay with flexible plate-like particles. The framework includes the study of inter-particle interaction at atomistic scale through free energy perturbation calculations with molecular dynamics simulations, from which the potential of mean force will be used to calibrate the coarse-grained force field to be used in meso-scale simulations. The modes of deformation and mechanical response of the mesoscopic systems are incorporated into a thermodynamically consistent constitutive model describing the small-strain elastic stiffness of illite clay at macroscopic level. The simulation results are compared with experimental results on the same material. The framework can provide good guidance on similar multiscale study on physico-chemical properties of clay to facilitate efficient material modification targeting for a greener civil engineering construction practice and has potential application in the investigation of other geomaterials.

BAYESIAN TWO-STAGE STRUCTURAL IDENTIFICATION WITH EQUIVALENT FORMULATION AND EM ALGORITHM

Jia-Xin Zhu[1] and Siu-Kui Au[1]*

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ABSTRACT

The use of structural models to simulate and predict structural performance has a longstanding history in engineering. When a model is established, the alignment of model prediction with observed data often relies on parameter selection that reflects model error. An efficient alternative to manual adjustment is Bayesian two-stage structural identification. In this approach, modal properties are first extracted from measured vibration data in Stage I, and then used for determining structural parameters in Stage II. With sufficient data for a globally identifiable problem, the computation often reduces to optimizing a ‘measure-of-fit’ function to yield the ‘most probable value’ (MPV) of parameters, and determining the Hessian to quantify identification uncertainty. Model error is inevitable as no model is perfect. The complexity of addressing it in the identification process calls for a proper computational strategy. In this spirit, assuming Gaussian model error, this work introduces a hypothetical yet mathematically equivalent formulation for the two-stage problem. The proposed formulation facilitates the development of effective algorithms for MPV using Expectation-Maximization techniques. By hypothetically treating the MPV of modal properties in Stage I as ‘data’ and considering model error as latent variables, the Q-function in the M-step can be expressed as a sum of two terms. These two terms can be optimized separately with respect to the structural parameters and model error parameters. The optimization of structural parameters reduces to a Stage II problem without model error, allowing the application of existing algorithms. By considering model error, the resulting posterior covariance matrix is found to give a more realistic quantification of identification uncertainty. The proposed method is investigated with synthetic data and lab data to assess the impact of model errors associated with sensor misalignment and model simplification, as well as the effects of the number of modes and measured degrees of freedom. It is also investigated with field data for reality tests.

Intelligent techniques and deep learning for bridge health monitoring
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A FAST NEWTON ALGORITHM FOR BAYESIAN MODAL IDENTIFICATION IN MULTIPLE-SETUP AMBIENT VIBRATION TEST

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ABSTRACT

Multiple-Setup ambient vibration test (AVT) is regularly adopted when the target is to obtain fine mode shapes with limited number of sensors. The accumulated data size (hours of dynamic responses) and the augmented modal parameters (easily reach hundreds) challenge the performance of modal identification algorithms for their speed and accuracy. A fast Newton algorithm is proposed in this paper to obtain a Laplace approximation of the posterior distribution of modal parameters following the formulation in Bayesian FFT method. The calculation of the Jacobian and Hessian in the Newton algorithm is based on a recently developed expectation-maximization (EM) algorithm, which builds the relation between the conventional likelihood function and the complete-data likelihood function. Since the function form of the complete-data likelihood function is much simpler than that of likelihood function, the Jacobian and Hessian can be obtained in semi-analytical forms using the calculus of complex matrix. The implementation details are presented, e.g., how to accommodate various constraints and how to ensure the positive semi-definiteness of the Hessian. The efficacy of this method is demonstrated using synthetic data from a shear frame model, followed by applications to various field test data from different structures. Results reveal that the proposed method surpasses existing algorithms by at least an order of magnitude in speed while achieves better accuracy. The proposed algorithm offers intuitive derivation, streamlined programming implementation, and eliminates the need for separate posterior covariance calculation, underscoring its practical advantages in multiple-setup AVT.

Origami/kirigami inspired structures and metamaterials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

DESIGN CONSIDERATIONS FOR THICK ORIGAMI WITH APPLICATION IN ADAPTABLE INFRASTRUCTURE

Yi Zhu[1] and Evgueni Filipov[1]*

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ABSTRACT

This work introduces a modular thick origami system for deployable large-scale structures with broad applications in rapid construction, disaster mitigation, adaptive building systems, and reusable infrastructure. More specifically, this talk will focus on kinematics and design considerations behind this proposed thick origami system. In this talk, we will first demonstrate the capability of our modular and uniformly thick origami (MUTO) system, showing that a MUTO package can sequentially reconfigure between densely packaging states, load carrying bridge states, column states, and bus stop states. The high-level adaptability of MUTO system is superior to state-of-the-practice and state-of-the-art deployable structure systems for buildings and infrastructure. After the demonstration of the superior adaptability, we will dive deep into kinematics and design considerations for these adaptable thick origami. We will derive thickness equations for developability and flat-foldability of origami vertices, and demonstrate how we can use them to identify potential origami designs. With these two equations, we investigated common thick origami vertices with four creases to ten creases, identifying potential candidates that can produce uniformly thick vertices. From the analyses, we can identify new degree-6 and degree-10 vertex that are not widely studied by the community. These new vertices could be integrated into new tessellations and patterns for future research. We believe the proposed equations provide new methods to design thick origami systems for applications beyond adaptable civil structures, such as deployable aerospace systems, biomedical devices, reconfigurable metamaterials, and many others.

Reference:
Yi Zhu, Evugeni T. Filipov, 2023, Modular and Uniformly Thick Origami for Large-Scale, Adaptable, and Load-Carrying Structures, (Under Review) (http://arxiv.org/abs/2310.03155)

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

UNCERTAINTY QUANTIFICATION OF NEGATIVE SAMPLES AND MODEL STRUCTURES IN LANDSLIDE SUSCEPTIBILITY CHARACTERIZATION BASED ON BAYESIAN NETWORK MODELS

Yichuan Zhu[1] and Sahand Khabiri[1]*

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ABSTRACT

Landslide susceptibility mapping (LSM) characterizes the landslide potential which is essential for assessing landslide risk and developing mitigation strategies. Despite the significant progress in LSM research over the past two decades, several long-standing issues, such as uncertainties related to training samples and model selections, remain inadequately addressed in the literature. In this study, we employed a physically based susceptibility model, PISA-m, to generate four different non-landslide data scenarios and combine them with mapped landslides from Magoffin County, Kentucky, for model training. We utilized two Bayesian Network model structures, Naïve Bayes (NB) and Tree-Augmented Naïve Bayes (TAN), to produce LSMs based on regional geomorphic conditions. After internal validation, we evaluated the robustness and reliability of the models using an independent landslide inventory from Owsley County, Kentucky. The results revealed considerable differences between the most effective model in internal validation, which used non-landslide samples extracted exclusively from low susceptibility areas predicted by PISA-m, and their unsatisfactory performance in external validation, highlighting the potential overfitting problem which is largely overlooked by previous studies. Additionally, our findings also indicate that TAN models consistently outperformed NB models when training datasets were the same, due to the ability to account for variable dependencies by the former.

Discrete models for the simulation of infrastructure materials
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

AN ENERGY REGULARIZATION SCHEME FOR THE MULTISCALE LATTICE DISCRETE PARTICLE MODEL

Yingbo Zhu[1] and Alessandro Fascetti[1]*

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ABSTRACT

Failure in quasi-brittle materials exhibits several multi-scale characteristics, such as meso-structural heterogeneities, crack coalescence, and damage localization. As a result of this, models that can provide a direct description of the random microstructure of these materials are of great practical and scientific relevance. However, the computational cost associated with such approaches is often prohibitive when simulating full-scale structural systems. For this reason, several multiscale approaches have been proposed in literature to represent the material at the mesoscopic level on a Representative Volume Element (RVE), and bridge such information to the macroscopic level by means of mathematical homogenization. In this manuscript, a modification of the Multiscale Lattice Discrete Particle Model (LDPM) model is proposed to address well-known issues associated with linking the macroscopic mesh configuration and the corresponding RVEs. The novel paradigm is based on an extension of the crack-band model that takes into account the element characteristic lengths of both the macroscopic mesh and the RVE, allowing for the formal quantification of the material properties to be assigned to the mesoscale LDPM simulations, with the ultimate goal of mitigating mesh dependence in the simulations. The feasibility and effectiveness of the proposed regularization scheme are verified by analyzing the response of plain concrete members with various mesh configurations (at both scales) under tensile and 3-point bending conditions and further validated by full-scale experimental data on different reinforced concrete structures.

Structural identification and damage detection
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

IMPURITY GAS MONITORING FOR SPENT NUCLEAR FUEL CANISTERS USING A VARIATIONAL AUTOENCODER (VAE)

Bozhou Zhuang[1], Bora Gencturk[1], Assad Oberai[1], Harisankar Ramaswamy[1], Ryan Meyer[2], Anton Sinkov[3] and Morris Good[3]*

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ABSTRACT

The spent nuclear fuel (SNF) canisters are stainless-steel containers that are used to store and/or transport SNF. To provide an inert environment, canisters are backfilled with helium after vacuum drying. However, the gas composition may change during a canister's interim storage period signifying degradation of the system integrity. For example, the fission gases may be released into the canister if the cladding of the fuel rods is breached. Additional impurities such as air and water vapor may also be simultaneously present due to insufficient vacuum drying. A determination of these gas impurities may be useful to identify potential deterioration of canisters. Therefore, monitoring the impurity gas is critical for the safety evaluation of SNF canisters. This study presents a variational autoencoder (VAE) method for detecting impurity gases in SNF canisters. Different impurity gases, argon and air, were backfilled to a sealed canister mock-up with helium. Ultrasonic transducers were mounted on the outside of the canister to probe the internal gas profile. The VAE was trained on the ultrasonic responses collected with pure helium (i.e., the healthy canister), and applied directly to the responses with impurity gases (i.e., the abnormal canister). Research results show that the VAE learns to reconstruct the pure helium signal well with small reconstruction errors. However, the VAE exhibits larger errors when it comes to reconstructing the impurity gas signal. This contrast highlights the capability of VAE to effectively differentiate the pure helium and impurity gases by producing different magnitudes of reconstruction errors. The latent space forms separable clusters for healthy and abnormal canisters. The clusters with higher impurity concentrations deviates further from the pure helium cluster. In addition, the trained decoder can generate high-fidelity pure helium signal by sampling from the standard Gaussian distribution and thus serves as a digital twin of the healthy canister. This combined experimental-computational non-destructive testing approach has potential applications in the safety evaluation of SNF canisters and radioactive waste management efforts.

Plan the future: Innovations in advanced cementitious materials and sustainability
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

MICROMECHANICAL MODEL FOR STRESS-STRAIN HYSTERESIS OF POROUS ROCKS UNDER HYDROSTATIC LOADING

Alvin Biyoghe[1], Yves-Marie Leroy[1] and Robert Zimmerman[1]*

[1]Imperial College

ABSTRACT

In 1965, Walsh [1] developed a model to explain stress-strain hysteresis in rocks under uniaxial loading, based on the mechanism of frictional sliding along the faces of microcracks. David et al. [2] extended that model by accounting for the closure of initially open cracks, and by extending the quantitative analysis to the full unloading portion of the stress-strain curve. The resulting model was able to fit the full loading-unloading stress-strain curve of several sedimentary and crystalline rocks, using a small number of parameters that each have a clear physical interpretation: uncracked rock modulus, crack density, initial aspect ratio, friction coefficient. Since these models ignore stress-field interactions between nearby cracks, they would predict no hysteresis under hydrostatic loading, since under macroscopic hydrostatic loading, the face of each crack would be subjected to normal traction without a shear component, and therefore would not be liable to slide. However, it is observed experimentally that a small amount of hysteresis does indeed occur during hydrostatic loading.

To extend this type of model to the hydrostatic regime, we assume that the rock contains spherical pores, with small microcracks dispersed throughout the rock “matrix” outside of the pores. In this way, a local deviatoric stress develops, despite the remote loading being hydrostatic. By use of Hashin’s spherical assemblage concept, we are able to analyze the behavior of a “unit cell” composed of a single pore surrounded by a cracked matrix. The mechanical behavior of the cracked shell is analyzed using the classical non-interactive scheme of Kachanov. The pore-fluid pressure is assumed uniform through the assemblage, in both the drained and undrained regimes. Analytical expressions for the bulk modulus at critical stages, including crack closure, and maximum forward- and reverse-crack-slipping, are presented. Several sets of experimental data from hydrostatic compression tests on dry sandstones and carbonates, taken from the recent literature, are used to validate the model, showing excellent agreement [3].

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Engineering Mechanics Institute Conference and Probabilistic Mechanics & Reliability Conference (EMI/PMC 2024)

Natural hazard assessment with monitoring, modeling, and uncertainty quantification
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

LANDSLIDE DISASTER EMERGENCY RESCUE BASED ON KNOWLEDGE GRAPH RESEARCH ON INTELLIGENT DECISION MAKING

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ABSTRACT

landslide disaster emergency decision-making can effectively reduce the subsequent disaster losses. However, grassroots governments or organizations primarily rely on response plans to carry out rescue operations, and are unable to swiftly make decisions based on a multitude of factors including geological strata properties, hydrological conditions, weather patterns, population distribution in affected areas, among others.The knowledge graph technology can effectively integrate multi-source data information of landslide disasters, and establish disasters entities and relations between entities. The landslide disaster knowledge graph collects data sources such as landslide data, standards and norms, and disaster investigation reports, and builds a NLP entity recognition training corpus in the field of landslide disaster emergency rescue. Through AI models such as BERT, CasRel, and ChatGLM, embedding representation of entities and their relationships such as disaster victims, emergency rescue, and affected areas are established in the high-dimensional semantic space of landslide disasters. The embedding representation made it possible a large number of landslide disaster text reports can be calculated.The landslide disaster knowledge graph reconstructs more than 2000 entities and complex relationships in the form of graph structures, and integrates knowledge such as landslide mechanisms, engineering prevention and control technologies, and emergency processes. The emergency rescue requirements such as disaster assessment and rescue are extracted from the landslide disaster knowledge graph to form a standard SWRL rule library, which provides auxiliary decision-making knowledge support for landslide disaster emergency rescue.