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

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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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)

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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.

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

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].

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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

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.

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

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 ($73^\circ \sim 77^\circ$ 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

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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.

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

Finite element modeling and simulation of train derailments and their role in assessing tank car safety
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

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.

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

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

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

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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

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

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

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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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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

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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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

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.

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

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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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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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

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

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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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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

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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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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

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]*

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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.

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

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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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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.

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

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.

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

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.

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

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

Alexandre Sac-Morane[1,2], Hadrien Rattez[1] and Manolis Veveakis[2]*

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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.

SIMULATING THE CONE PENETRATION TEST IN UNSATURATED SOILS USING COUPLED DISCRETE ELEMENT METHOD AND MULTIPHASE LATTICE BOLTZMANN METHOD

Sina Sadeghi[1] and Reihaneh Hosseini[1]*

[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.

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

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

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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)

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

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]*

[1]The University of New Mexico

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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[4]Universidad de Concepción

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

Subhrangsu Saha[1] and Oscar Lopez-Pamies[1]*

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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.

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

Soumya Sahoo[1]

[1]*IIT Bhubaneswar*

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.

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

ERROR-IN-CONSTITUTIVE RELATION (ECR) FRAMEWORK FOR THE WAVE-BASED CHARACTERIZATION OF LINEAR VISCOELASTIC SOLIDS

Marc Bonnet[1], Prasanna Salasiya[2] and Bojan Guzina[2]*

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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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[1]Simpson Gumpertz & Heger

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.

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

REINFORCEMENT LEARNING-BASED BRIDGE INSPECTION MANAGEMENT

Xin Zhang[1], Manuel Salmeron[1], Lissette Iturburu[1], Xiaoyu Liu[1], Benjamin Wogen[1] and Shirley Dyke[1]*

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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

Manuel Salmeron[1], Herta Montoya[2], Edwin Patino[1], Ingrid E. Madera Sierra[3] and Shirley Dyke[1]*

[1]Purdue University
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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.

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

INVESTIGATING THE INFLUENCE OF PRE-EXISTING MICRO & MACRO CRACKS ON THE STIFFNESS OF BEAM STRUCTURES UNDER QUASISTATIC LOADING THROUGH PERIDYNAMICS

Sanchit Saxena[1], Suman Kumar[2] and Hrishikesh Sharma[3]*

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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.

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

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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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[2]Toggle industries

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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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.

[1] Schär, S. et al. "Emulating the dynamics of complex systems using autoregressive models on manifolds (mNARX)", Mech. Syst. Signal Proces., 2023

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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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]*

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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.

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

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

PROPER GENERALIZED DECOMPOSITION FOR TOPOLOGY OPTIMIZATION OF PROBLEMS WITH SEPARABLE GEOMETRY FOR MINIMAL ELASTIC OR THERMAL COMPLIANCE

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[1]KU Leuven

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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[2]Coreform LLC

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

Abigail Schmid[1], Alireza Doostan[1] and Fatemeh Pourahmadian[1]*

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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.

Towards resilient communities: Improvements in natural hazard risk assessment using data-driven methods
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

A MACHINE LEARNING APPROACH FOR HURRICANE-INDUCED FLOOD DEPTH ESTIMATION: A CASE STUDY ON HURRICANE HARVEY

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[1]University of Florence
[2]Fuzhou University
[3]University of L'Aquila

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.

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

CHALLENGES IN HYDRO-REAL-TIME HYBRID SIMULATION TO EXAMINE THE RESPONSE OF FLOATING OFFSHORE WIND TURBINES

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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.

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

EFFECT OF DIFFERENT TORNADO CHAMBERS ON VORTEX STRUCTURE AND VORTEX PARAMETERS

Rathinam Selvam[1]

[1]*University of Arkansas*

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.

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

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

Sandeep Acharya[1] and Debarshi Sen[1]*

[1]Southern Illinois University Carbondale

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]*

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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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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

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

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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%.

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

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.

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

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.

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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.

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

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

Shoham Sen[1], *Liping Liu*[2] *and Pradeep Sharma**[1]

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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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[1]Texas A&M University

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.

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

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.

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

MESOSCOPIC DISCRETE MODELING OF TENSION STRENGTH REDUCTION OF CONCRETE TENSION STRENGTH DUE TO FINE FIBER CONTENT INCREMENT

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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.

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.

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

A LARGE-SCALE SYNTHETIC 3D POINT CLOUD DATASET FOR VISION-BASED BRIDGE CONDITION ASSESSMENT

Mingyu Shi[1], Hyunjun Kim[2] and Yasutaka Narazaki[1]*

[1]Zhejiang University
[2]Seoul National University of Science and Technology

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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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.

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 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.

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

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

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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.

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

A SUB-STRUCTURING APPROACH TO OVERCOME MODEL LIMITATIONS FOR INPUT-STATE ESTIMATION OF OFFSHORE WIND TURBINES

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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.

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

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

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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.

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

NUMERICAL MODELING OF TRUCK-ELECTRIFICATION-INDUCED EXCESS FUEL CONSUMPTION IN HIGHWAY FLEXIBLE PAVEMENTS

Johann Jhanpiere Cardenas Huaman[1], Aditya Singh[1] and Imad Al-Qadi[1]*

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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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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

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.

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

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.

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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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

MULTISCALE STRUCTURAL OPTIMIZATION FOR APPLICATIONS IN THERMAL STABILITY AND ACTUATION

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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

ADVANCED COMPUTATIONAL AND DEEP LEARNING ALGORITHMS FOR MODELING AND DESIGN OF MATERIALS

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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

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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

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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.

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

MULTIPLEXED LASER ULTRASONIC IMAGING VIA THE LINEAR SAMPLING METHOD

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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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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

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

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

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

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

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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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[1]Southeast University

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.

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

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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[2]University of Michigan

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.

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

DATA-DRIVEN PROCESS UNCERTAINTY ANALYSIS OF STOCHASTIC LACK-OF-FUSION IN LASER POWDER BED FUSION

Vamsi Subraveti[1] and Caglar Oskay[1]*

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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.

CHARACTERIZING COUPLED EXTREME WIND-WAVE LOADS ON OFFSHORE WIND TURBINES USING LARGE EDDY SIMULATIONS

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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

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[2]University of Wisconsin–Madison

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

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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.

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

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.

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

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 eigen-values/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.

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

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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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.

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

MITIGATING VORTEX-INDUCED VIBRATION CHALLENGES IN LONG-SPAN BRIDGES: A COMPREHENSIVE STUDY OF CHONGQI BRIDGE

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[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

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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

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]*

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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.

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

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

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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

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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.

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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

Merab Svanadze[1]*

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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*

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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

Ann Sychterz[1]

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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.

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

NUMERICAL SIMULATION OF THE LATERAL BEHAVIOR OF 3D-PRINTED HEMPCRETE (3DPH) WALLS

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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.

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

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

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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

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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.

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

A MACHINE LEARNING-BASED SURROGATE MODELING APPROACH FOR SEISMIC RESPONSE ANALYSIS OF SOIL-STRUCTURE SYSTEMS

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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.

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

Multi-fidelity methods and machine learning for uncertainty propagation, inference, and optimization
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

ENHANCING DATA EFFICIENCY AND ACCURACY IN FINITE ELEMENT ANALYSIS USING MULTI-FIDELITY GRAPH NEURAL NETWORKS

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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.

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

SOIL-STRUCTURE SYSTEM IDENTIFICATION USING BAYESIAN FINITE ELEMENT MODEL UPDATING

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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.

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

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.

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

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

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.

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

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

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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Infrastructure assessment automation with robotics, deep learning and digital twins
May 28-31, 2024, Palmer House Hotel, Chicago, IL, United States

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.

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.

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.

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

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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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.

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

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

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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

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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.

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

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

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.

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

RISK-BASED DESIGN OF INERTER VIBRATION ABSORBERS UTILIZING EMBODIED ENERGY SUSTAINABILITY CRITERIA

Parisa Toofani Movaghar[1], Alexandros Taflanidis[1], Agathoklis Giaralis[2] and Dimitrios Vamvatsikos[3]*

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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.

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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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.

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

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.

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

CONNECTOR AND BEAM LATTICE (CBL) MODEL FOR THE SIMULATION OF WOOD UNDER HIGH STRAIN RATES

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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

Eleonora Maria Tronci[1], Anna Haensch[2], Bridget Moynihan[2], Babak Moaveni[2] and Eric Hines[2]*

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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]*

[1]Louisiana State University

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

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]*

[1]University of Twente

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

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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).

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

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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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

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

ELECTRONIC, ELASTIC AND PHONON PROPERTIES OF WN2 (194 & 187) BY DFT APPROACH

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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

Justin Unger[1], Timothy P. Weihs[1] and James Guest[1]*

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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

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[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.

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[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]*

[1]University of Naples Federico II

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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[1]*Universidad Iberoamericana Ciudad de México*

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.

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

LEARNING MODELING ERRORS VIA A MACHINE-INFUSED BAYESIAN MODEL UPDATING APPROACH

Mohammad Valikhani[1], Kasra Shamsaei[1] and Hamed Ebrahimian[1]*

[1]University of Nevada, Reno

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

Mohammad Valikhani[1], Hamed Ebrahimian[1] and Babak Moaveni[2]*

[1]University of Nevada, Reno
[2]Tufts University

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]*

[1]Indian Institute of Technology Madras
[2]Lawrence Livermore National Laboratory
[3]Ecole Polytechnique Federale de Lausanne
[4]ExxonMobil Technology and Engineering

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]*

[1]*Worcester Polytechnic Institute*

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

Sina Youssefian[1], Mobin Vandadi[2], Joseph Jakes[3] and Nima Rahbar[2]*

[1]Advanced Semiconductor Materials Lithography
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[3]Forest Products Laboratory

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.

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

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]*

[1]KU Leuven
[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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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

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.

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

3D RADIANCE FIELD-BASED NOVEL VIEW ANOMALY DETECTION IN INFRASTRUCTURE

Subin Varghese[1] and Vedhus Hoskere[1]*

[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

Themistoklis Vargiemezis[1] and Catherine Gorlé[1]*

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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.

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

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

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]*

[1]Los Alamos National Laboratory

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

Swetha Veeraraghavan[1]

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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.

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]*

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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.

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

AN AEROELASTIC EMULATOR COMPRISING SHAPE, FREQUENCY, AND MEAN ANGLE OF ATTACK FOR THE AERO-STRUCTURAL DESIGN OF BRIDGES UNDER NON-SYNOPTIC WINDS.

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

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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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.

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

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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.

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

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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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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

A PHYSICS-BASED CRYSTAL PLASTICITY MODEL WITH APPLICATIONS IN SIMULATION OF MICROPILLAR COMPRESSION AND STRENGTHENING EFFECT OF MULTILAYERED COPPER-GRAPHENE NANOCOMPOSITES

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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

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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.

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

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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