# Synergy between Multiphysics/ Multiscale and Artificial Intelligence

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ABSTRACT

The motivation of this talk is to investigate the complementarity of classical multi-physics/multi-scale approaches and model building approaches based on the use of artificial intelligence algorithms.

The knowledge accumulated through the long-term efforts of computational mechanics experts provides an a priori selection of efficient reduced models built with appropriate assumptions and kinematic constraints. Classical structural models are also proving to be very useful for building relevant multi-scale and multi-physics models.

In parallel, there are many advances in the use of Artificial Intelligence and statistical data analysis algorithms in solid and structural mechanics. How can such approaches be developed in synergy? Can they benefit from each other's advances? Can model building skills be reduced to the application of artificial intelligence algorithms?

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איגוד ישראלי לשיטות חישוביות במכניקה
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# All-at-once transient structural analysis and design optimization with application to seismic retrofitting

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ABSTRACT

The approaches for transient structural optimization typically have an iterative nature. In every iteration, expensive time-history analyses are performed to evaluate the system response after each design update. This presentation introduces a novel optimization-based approach for seismic retrofitting. The presented approach does not require the computation of time history analyses. The sizing and placement of the dampers are defined using a simultaneous analysis and design optimization approach based on nonlinear programming. In this approach the equations of motion are treated as equality constraints of the optimization problem. Consequently, design sensitivity analysis methods are not needed to calculate the gradients of the objective and constraint functions. Different design scenarios are discussed: structures with a linear behavior retrofitted with linear fluid viscous dampers, and structures with hysteretic behavior retrofitted with linear or nonlinear fluid viscous dampers. The optimization variables include the damping coefficients of the dampers and the structural response over time. In other words, the structural response and the structural design are optimized simultaneously, all at once. The numerical results demonstrate that the proposed approach can solve complex design optimization problems using reasonable computational resources and time. It is also shown that, thanks to the proposed approach, additional constraints can be incorporated in the problem formulation with minimal modeling effort, and without the need to develop additional sensitivity analyses for computing the gradients of the added constraints.

# Combined Bistability-Latching Criteria in Pre-Pressured and Electrostatically Actuated Curved Microplates

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## ABSTRACT

In this study, an electrostatically actuated microplate is considered with additional constant transverse mechanical pressure. The added load is taken into account for the derivation of combined bistability and latching criteria, which includes an additional configuration, not apparent in the electrostatically actuated and pressure-free counterpart. The plate is studied using two reduced-order (RO) models. The first is based on the Föppl von-Kármán model, and the other is based on Berger's approximation, from which both bistability and latching conditions were be extracted. The study has found that for such a loading scheme, bistability and latching are intertwined. More specifically, it was found that latching can hamper bistability, making it an integral part of the resulting criteria. The study has found that in the presence of electrostatic displacement-dependent load, the added mechanical, displacement-independent, load, will bear a non-linear effect, where bistability may be present but not guaranteed. As such, the condition for bistability is a necessary condition, and the condition for latching, a sufficient one.

The RO models that describe the behaviour of the plate were solved using an upgraded version of the arc-length method, that also includes a stability analysis. The reason for the added analysis is twofold. Firstly, the plate must first undergo a mechanical analysis, which will end once the plate converges to a configuration which corresponds to the load bearing upon it. However, not all configurations are created equal, since the calculation may encounter an unstable configuration that corresponds to the load $P$. Something that cannot occur once the electrostatic load is added. Secondly, the inclusion of stability analysis enables one to disclose limit points without additional extremums that form at higher elevations. The transition from mono- to bistability was therefore found to depend not only on the geometry, but also on the pressure exerted on the plate. In other words, while mechanical load alone seemed to be invariant to bistablity, depending solely on the geometry of the plate, the presence of a nonlinear load adds to the effect mechanical load has on bistability.

The resulting criteria and characterisation paradigm can be of service when approaching the design of threshold pressure sensors. Depending on the stability profile of the structure (i.e., mono- or bistable), it is possible to know if a microplate has surpassed a desired pressure to become bistable. Alternatively, a bistable microplate will become monostable if it crosses the condition with rising pressure, positioning the plate at a monostable configuration/phase. Due to the generality of the approach and methodology in the current study, it can be applied to other types of plates, such as rectangular or plate strips. Ultimately, the inextricable link between pressure and bistability, present under electrostatic load, allows one to track changes in equilibrium configurations and ascertain if a microplate experiences a pressure that either allows for bistability, or not.

# Identifiability of anisotropic hyperelastic parameters from indentation experiments

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ABSTRACT

Patient-specific biomechanical finite element analyses (FEA) are widely employed to simulate the mechanical behavior of human tissues and their interaction with medical devices. These simulations play a critical role in the design of prostheses, orthoses, and surgical planning by incorporating patient- and location-specific tissue mechanical properties. Accurate modeling requires individualized material parameters, which are often challenging to obtain in-vivo due to the invasive nature of standard experimental methods. Non-invasive material characterization methods, such as indentation, often result in multiple sets of seemingly optimal parameters, known as the non-uniqueness problem, making reliable predictions difficult for other loading scenarios [1].

This study investigates the feasibility of uniquely identifying hyperelastic transversely isotropic soft tissue parameters through macro-scale indentation experiments. A combined numerical and experimental approach was adopted, utilizing a spherical indenter to indent a custom-made soft transversely isotropic composite material, while simultaneously measuring the indentation forces and full-field surface deformations. Inverse FEA was then applied to extract homogenized material parameters from these measurements. To assess parameter certainty, we introduced an enhanced sensitivity analysis method based on the Hessian approximation of the objective function, enabling quantification of confidence intervals around identified parameters [2].

Results revealed confidence intervals of ±7.5% for isotropic parameters and ±33% for anisotropic parameters in the test case. Additionally, individual composite components were characterized and incorporated into an FEA model of the composite, validating the material parameters obtained via inverse FEA. This study demonstrates the potential for improved reliability in non-invasive material characterization methods, paving the way for more precise patient-specific biomechanical modeling.

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# קירוב טריגונומטרי לא מחזורי

פרופ' הלל טל-עזר

אפקה – המכללה האקדמית להנדסה בתל אביב

# NON-PERIODIC TRIGONOMETRIC APPROXIMATION

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Trigonometric functions are typically the ideal basis for approximating periodic functions. However, when dealing with non-periodic functions, polynomials are more commonly employed. This talk will highlight the limitations of polynomial approximations and introduce a novel set of basis functions: Non-Periodic Trigonometric Functions. These new functions overcome the shortcomings of polynomial approximations and can approximate analytic functions with spectral accuracy. We will demonstrate that these basis functions are optimal for resolving band-limited functions, requiring only two points per wavelength, in accordance with the Nyquist criterion. Furthermore, these basis functions show significant promise in numerical integration, yielding higher accuracy compared .to Legendre quadrature

# Identification of an Elastic Inclusion Using a Time-Dependent Adjoint Method

## זיהוי אינקלוזיה אלסטית באמצעות שיטת צמוד תלוית-זמן

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**Key Words:** *Inclusion, Inverse problem, Adjoint method, Gradient, Shape identification, damage identification, Elastodynamics.*

ABSTRACT

The inverse problem of identifying an inclusion, a small region in the medium where the material properties are significantly different than those of the surroundings, is considered. The inclusion properties to be identified are the material properties - elastic moduli and mass density, and the shape (the interface curve that separates the inclusion from the rest of the domain). This work extends [1] in two ways: first, the governing equations are the equations of elasticity rather than the scalar wave equation, second, the scatterer is an inclusion and not a hole. In the proposed method, the identification is performed using full waveform inversion. Sensors measure the waves generated by known tractions, then, a two-stage iterative process is performed to find the inclusion's properties that best matches the measurements. The adjoint method is used for its efficient calculation of the gradient of the misfit function. The unknown interface is defined by a parametric representation, that is completely general and does not make any preliminary assumptions about the scatterer geometry. The performance of the proposed method is demonstrated via numerical examples, starting with material property identification alone, followed by shape identification alone, ending with simultaneous identification of both material properties and shape. All numerical experiments were performed on inclusions with varying contrasts: inclusions with material properties close to those of the background, and inclusions with significantly different material properties from the background. It is concluded that the contrast of the inclusion has a significant impact on the success of the identification.

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# Computational Probabilistic Approach for Assessing the Residual Axial Capacity and Deflection of Steel Wide-Flange Columns Subject to Blast Loading

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**גישה חישובית הסתברותית להערכת התסבולת הצירית השיורית וההזזות של עמודי פלדה רחבי אגף תחת עומסי הדף**

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## ABSTRACT

This research presents a computational approach to develop probabilistic models for steel wide-flange columns subjected to static axial load and transverse far-field blast loading, causing flexure about on their strong bending axes. The study utilizes the ANSYS LS-DYNA software to simulate the structural responses of several steel sections. A total of 160 finite element (FE) simulations were conducted, incorporating various Axial Load Ratios (ALRs) and diverse blast load profiles to capture a wide range of potential scenarios. The numerical models were validated against two experimental datasets. For this validation, a plastic kinematic material model with strain rate effects was employed, along with selectively reduced integrated brick elements, to capture the nonlinear behavior of the columns under blast loading. Following validation, these modeling techniques were applied to all subsequent simulations.

Dimensionless influential explanatory functions were used to develop robust probabilistic models that predict the residual axial capacity and maximum deflection of the columns after exposure to far-field detonations. The stepwise deletion approach was employed to identify the most significant explanatory functions, guided by Bayesian inference and posterior statistics, to ensure the models' reliability and accuracy. The probabilistic formulations developed in this study comprehensively account for both aleatoric and epistemic uncertainties. These include, among others, uncertainties in material properties, geometric structural configurations, and strain rate effects. The resulting equations offer a promising methodology for assessing the structural integrity of steel wide-flange columns under blast loading. They provide valuable insights for making informed decisions regarding building occupancy, retrofitting measures, and the design of critical facilities such as industrial buildings, fireworks facilities, hospitals, defense structures, and petrochemical plants.

For future work, we plan to numerically validate the experimental results previously obtained for close-in detonated steel sections and evaluate their residual axial capacity after damage (See FIG 1).

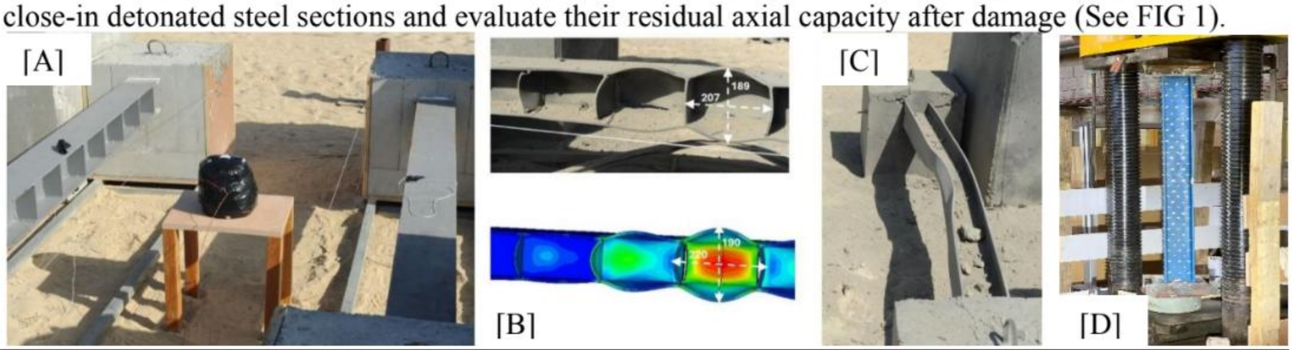


FIG 1 (A) EXPERIMENTAL SETUP OF CLOSE-IN DETONATIONS (B) DAMAGED SECTION WITH STIFFNERS (C) DAMAGED SECTION WITHOUT STIFFNERS (D) AXIAL CAPACITY TEST

**Investigating cold compaction of Al-$TiB_2$ and Al-SiC powder mixtures using finite element modeling validated by compaction experiments**

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ABSTRACT

In recent decades, composite materials based on a metallic matrix reinforced with ceramic particles has replaced traditional monolithic alloys in many applications in the aerospace, automobile, and nuclear industries. These composites offer the potential of enhanced thermal and mechanical properties and greater durability in service. An attractive method for the fabrication of metal-ceramic composites is the use of cold compaction of a metal-ceramic powder mixture followed by sintering at high temperatures. During the compaction stage, the time-dependent hydrostatic stress at each material point governs the final density distribution of the component. Large-density gradients can result in defective components with low thermal conductivity and reduced ductility and strength. As a consequence, predicting the density distribution during the compaction stage is critical. Although many analytical models can provide average values of the compact density, due to the complex non-linear nature of the compaction process, numerical methods must be utilized to obtain local values of density.

This research focused on investigating the cold compaction process of Al-$TiB_2$ and Al-SiC powder mixtures (0-15% volume fraction of $TiB_2$ and SiC in the Al were considered) using finite element analysis in conjunction with compaction experiments. The powder mixture was assumed to behave like a porous media and was modeled using the Gurson-Tvergaard-Needleman (GTN) constitutive model. A density-dependent elastic response of the powder mixture was also incorporated using a user-defined sub-routine in the commercial code ABAQUS. Convergence studies were conducted for solution verification and compaction experiments were used to both identify the GTN model parameters and to validate the computational models. By comparing the computations to the compaction experiments, it is demonstrated that a density-dependent elastic response is required for the GTN model to represent the observed initial part of the compaction curve accurately where the relative density is low. The study also reveals that the GTN model parameters $q_1$ and $q_2$ can be correlated to the volume fraction of the ceramic reinforcement particles. From a practical point of view, it is also shown that increasing the volume fraction of the ceramic reinforcement, although increasing initial powder density results in greater final local density gradients.

**A combined damage-viscoplasticity and phase field model for brittle materials under dynamic loading**

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ABSTRACT

Phase field method is a widely used approach to model fracture in computational mechanics. Its attraction comes from the ability to simulate crack initiation, propagation, and branching without remeshing or introduction of additional modelling entities, such as discontinuity variables in the XFEM. The main drawback of this method is the computational labor due to dense meshes required to reach high accuracy. Moreover, practice has shown that the phase field approach does not perform well in modelling brittle materials under compression. More precisely, it is challenging to predict realistic failure modes for heterogeneous concrete and rock under uniaxial compression.

In contrast, the continuum damage-plasticity approach does not suffer from this shortcoming. Therefore, in the present study, we combine the phase field approach with a damage-viscoplasticity model so that both the tensile and compressive failure types can be tackled with a single model. The viscoplasticity part is formulated with the consistency approach by Wang (1997), while the stress states leading to inelastic strain and damage are indicated by the Mohr-Coulomb criterion. Moreover, since we aim to solve dynamic problems, a rate dependent formulation of phase field method is presented. For this, we employ the so-called hybrid formulation of the phase field theory, which enables using an application specific crack driving force for brittle materials in dynamic tension. In the present case, this force depends on the positive part of the hydrostatic stress and the rate-dependent tensile strength (as the threshold value). We also present a scheme to decide, based on the trial stress state, which kind of failure process is taking place, a compressive failure requiring return mapping on the yield surface or an update of the crack driving force leading to increase of the phase field variable (or both simultaneously).

The global problem is solved by marching explicitly in time solving first the phase field problem and then updating the mechanical field variables based on the modified Euler method. The present approach is demonstrated in simulations of uniaxial tension and compression tests, as well as the dynamic Brazilian disc test on rock.

## The Immersed Boundary Method: A Preconditioned SIMPLE Approach for Moving Bodies

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ABSTRACT

In this talk we will present an efficient direct-forcing immersed boundary method (IBM) for moving boundary simulations. In the recently suggested SIMPLE approach for IBM [1], an intermediate velocity field is first calculated, followed by a generalized saddle-point system in which the pressure and force corrections are coupled. In [1], this saddle-point system was addressed by utilizing a standard block-reduction, solving first for the force correction field from which the pressure correction field is next calculated. However, this method was prohibitively expensive for moving bodies, as the dual Schur-complement used there is a product of an inverse Laplacian with coupling blocks that change at each time step. Hence, it is impractical for realistic 3D problems to form the Schur-complement, that must be rebuilt in each time step.

In this work, we suggest performing the block reduction the other way around, solving first the primal Schur-complement for the pressure correction field, from which the forces correction field can be calculated. Together with an approximation of the regularization block by a scalar matrix, the primal Schur-complement is formed by a matrix product, without inversion of any block. However, the obtained matrix is large and ill-conditioned, and hence to make the method scalable, we solve it iteratively using an efficient preconditioner. To this end, we take the Laplacian as a preconditioner for the primal Schur-complement of the pressure-force corrections system. We prove rigorously that the Laplacian is spectrally equivalent to the primal Schur-complement. That is, the preconditioned system can be solved by a constant number of Krylov iterations, regardless of the grid size, Reynolds number, and time step. The method's performance is validated through simulations of flow around a periodically oscillating sphere in a three-dimensional box. The memory requirements are notably low, allowing precise moving boundary simulations to run on standard workstations.

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# The Initial Stages of a Pressurized Hydrogen Jet Release: Detailed Investigation via High-Fidelity Numerical Simulations

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ABSTRACT

The sudden release of pressurized hydrogen as a jet into a reactive environment can lead to complex fluid dynamics processes, including spontaneous ignition and turbulent jet formation. This phenomenon can occur in various engineering applications, such as hydrogen storage in high-pressure vessels, hydrogen refueling stations, and industrial storage sites. In order to improve safety measures for these applications, it is essential to understand the complexities of the highly turbulent hydrogen jet flow during the early stages of the release. Hence, we investigate this phenomenon via high-fidelity massively parallel 3-D numerical simulations utilizing the Implicit Large Eddy Simulation (ILES) method. We specifically analyze how the initial pressure ratio between hydrogen and atmospheric air, as well as nitrogen released into atmospheric nitrogen, affects the characteristics of turbulent jet flow and mixing. To better understand the initial transient flow behavior, our focus is on conditions where spontaneous ignition is not possible. Consequently, for hydrogen released into air, we investigated various initial pressure ratios of 60, 30, 15, and 7.5, using jet release diameters of 1.5, 3, and 6 mm. For nitrogen released into nitrogen, we examined pressure ratios of 60, 30, 15, and 7.5, with a 3 mm jet release diameter. To validate our simulations against experimental results, first, we conducted two additional simulations of nitrogen released into nitrogen at pressure ratios of 100 and 15, utilizing a 7 mm jet release diameter. Additionally, we validated the steady-state Mach disk positions predicted by our simulations against experimental results from the literature, demonstrating excellent agreement. We found that the time for the Mach disk to reach steady-state decreases with a lower initial pressure ratio. We also examined how the initial pressure ratio and varying jet release diameters affect the self-similarity of the turbulent hydrogen jet. Our findings show that a larger jet release diameter enhances the jet's self-similarity, whereas for the smallest diameter, the jet is non-self-similar at early stages across different pressure ratios. Moreover, we observed that the jet loses its self-similar behavior more quickly as the initial pressure ratio decreases. Lastly, we investigate the mixing shear layer created by the turbulent jet flow. Our results reveal that higher initial pressure ratios result in a thicker shear mixing layer and a broader temperature range. Our findings are designated to aid in refining hydrogen injection systems and enhancing safety standards for high-pressure hydrogen storage.

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**אופטימיזציה של ביצועי משאבת אימפדנס ע"י שימוש בסימולציות נומריות במערכות משולבות זרם-מבנה**

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**Optimizing Impedance Pump Performance Using Numerical Simulations of Fluid-Structure Interaction Systems**

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## ABSTRACT

Impedance pumps, which utilize a valveless mechanism driven by fluid-structure interaction (FSI), have garnered significant attention due to their potential applications in biomedical devices and microfluidic systems. This research focuses on novel aspects of this mechanism, specifically the effects of multi-pincher configurations and channel geometry, which have not been previously explored in depth. Through numerical simulations, the influence of the number, positioning, and synchronization of pinchers on net flow generation and overall pump efficiency was examined. The results reveal how varying the amplitude and synchronization of pinchers affects the net flow rate (NFR). For example, using one pincher with a 50 Pa amplitude resulted in an NFR of 0.32 ml/min, while increasing the amplitude to 100 Pa produced a significantly higher NFR of 2.45 ml/min. Additionally, employing two pinchers with an ideal phase difference between their pinching times resulted in an NFR of 2.65 ml/min, even at a 50 Pa amplitude, demonstrating the enhanced performance of synchronized multi-pincher setups. This work also investigates the impact of rectangular channel geometry on wave dynamics and flow patterns, offering new insights into optimizing impedance pumps for improved stability and efficiency in complex fluidic environments.