

MECHANICAL ENGINEERING | PHYSICS |
PRESERVATION OF THE ARCHITECTURAL
HERITAGE | STRUCTURAL, SEISMIC
AND GEOTECHNICAL ENGINEERING |
URBAN PLANNING, DESIGN AND
POLICY | AEROSPACE ENGINEERING |
ARCHITECTURE, BUILT ENVIRONMENT
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ARCHITECTURAL, URBAN AND INTERIOR
DESIGN | BIOENGINEERING | DATA ANALYTICS
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CHEMICAL ENGINEERING | INFORMATION
TECHNOLOGY | MANAGEMENT ENGINEERING
| MATERIALS ENGINEERING | MATHEMATICAL
MODELS AND METHODS IN ENGINEERING



Chair:
 Prof. Dario Angelo
 Maria Coronelli

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Objectives of the Doctoral Program

Structural, Seismic and Geotechnical Engineering (SSGE) encompasses disciplines and techniques allowing understanding, modeling and controlling the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials, materials for micro-systems and metamaterials), (b) structural systems (from civil and industrial structures and infrastructures to bio-mechanical systems and micro-systems) and (c) environment-structure interaction.

Deeply-rooted in the Civil Engineering, SSGE focuses on environmental actions, either external (such as earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction. The methods developed within the domain of SSGE apply to different scales and different physical process and, as such, are of great importance also in other technical-scientific fields, whenever understanding and controlling structural and material behavior is necessary to guarantee design reliability and structural safety, as well as serviceability and durability. Many are the themes arising in connection to SSGE: from tall buildings and bridges to industrial bio-mechanical and micro-electromechanical systems; from off-shore structures and dams to the rehabilitation of historical buildings; from seismic design and structural dynamics to the behavior of geomaterials and new engineered metamaterials.

Within this framework, the main goal of our Graduate School is to promote the advancement of knowledge especially in the fields of: (a) innovation in structural materials and structures; (b) structural safety under highly-variable actions; (c) behavior of geomaterials and surface structures.

We pursue this goal by offering our PhD Candidates an advanced, research-oriented background, based on both the pivotal role of Structural Engineering and the multi-disciplinary nature of Seismic and Geotechnical Engineering.

Contents of the Doctoral Program

Attainment of a PhD in Structural, Seismic and Geotechnical Engineering is conditional to: a minimum of three full-time years' study and research activities; the development of a PhD thesis; the achievement of the minimum credits required in terms of PhD courses.

Candidates are offered a variety of advanced courses on different topics, including mechanics of soils, materials and structures; computational and experimental methods; structural dynamics and earthquake engineering.

The study plan includes courses and seminars given by scientists, experts and researchers active either at the Politecnico di Milano or in other Italian and foreign Universities, research institutions and high-tech companies.

During their studies, PhD Candidates should develop their own original research work, consistent with the main disciplines dealt with in the Doctoral program, which will be reported in the PhD thesis.

The thesis should clearly state the goals of the research work, explaining the relation with the

state-of-the-art, the used methods and the original results obtained.

The PhD research is developed under the guidance of a supervisor.

In order to widen and improve their research experience, PhD Candidates are strongly encouraged to spend a period abroad in one of the many Universities and research centers related to the Politecnico di Milano.

At the same time, the PhD School supports foreign scholars to give short courses and seminars in Milan, so that our PhD Candidates can constantly benefit from the opportunity to interact with the international scientific community.

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METAMATERIALS AS UNDERWATER ACOUSTIC BARRIERS

Marco Antonacci – Supervisor: Valentina Zega

Co-Supervisors: Varvara Kouznetsova, Ondrej Rokos, Massimiliano Cremonesi

Offshore wind turbines installation produce a very high amount of noise which is propagating in water in a wide area surrounding the site. It can reach up to 200 [dB] if unmitigated. As such, solutions to reduce the noise propagating in the surrounding water must be implemented when installations take place, to avoid permanent damages to fish and mammals. Currently available solutions are able to reduce the noise of maximum 20 [dB] and are still associated to high costs for handling and deployment, i.e. bubble curtains. It follows that the research for a better and more manageable noise reducing solution is evident. In this thesis, an alternative solution, composed of Locally Resonant Acoustic Metamaterials (LRAMs) directly attached to the pile, is employed. Metamaterials are structures which are able to showcase features not available in common materials, such as bandgaps, i.e. regions in frequency where waves in the structure cannot propagate. By employing the proposed methodology, the aim is to verify the performances of LRAMs, alongside proposing a more economical and manageable solution. After the selection of a case study,

a numerical model capable of evaluating the dangerous radial modes associated to the selected pile was developed. Then, the alternative solution based on LRAMs was developed by selecting some starting resonator shapes and optimizing them using a generic algorithm-based scheme, which promotes designs with wider bandgaps at the frequency where the most dangerous radial modes were identified. Once optimized, numerical simulations were performed, and a numerical reduction of 12 [dB] was found. To further reinforce the bounty of this result, an experimental validation at a smaller scale than the real one was conducted during the stage at PhononicVibes. After having selected a proper tube for testing, resonators which target radial modes were designed and tested in air. Results proved a reduction of the radial acceleration of 20 [dB]. Tests were performed also in water after a re-tuning process of the resonators, since water has an effect on radial modes equivalent to that of an addition of mass. Tests in water also showcased the power of the proposed barrier, reducing the pressure of propagating waves of 16 [dB].

ADVANCED CEMENTITIOUS COMPOSITES FAÇADE ELEMENTS: STATIC/CYCLIC BEHAVIOUR

Sara Basci – Supervisor: Matteo Colombo

Advanced cementitious materials, such as High Performance Fiber Reinforced Concrete (HPFRC) and Ultra High Performance Fiber Reinforced Concrete (UHPC), are increasingly used in non-structural applications like facade panels due to their superior mechanical properties, aesthetic versatility, and ability to achieve slender profiles. However, the design and application of these materials face significant challenges, including tensile behaviour characterization, size effect in bending, and cyclic performance. These aspects are critical for developing reliable design approaches, especially considering that the dimensions and cyclic performance of panels significantly influence their practical use. Large panels are often preferred to meet aesthetic and construction efficiency requirements, as they expedite installation processes. At the same time, building envelopes are subjected to cyclic loads, such as wind action. To address these challenges, three experimental campaigns were conducted. The first investigated the tensile behaviour of HPFRC and UHPC through direct and indirect tensile tests, highlighting

the influence of testing configurations on material characterization (Fig. 1). The second focused on size effects in bending, using four-point bending tests on thin HPFRC slabs with varying dimensions. The results demonstrated a significant size effect, with reduced nominal stress as the length of specimens increased, underscoring the need to account for these effects in design (Fig. 2). Furthermore, Weibull's theory was proposed as a representative model to describe this phenomenon. The third campaign examined cyclic behaviour, performing static and cyclic tests on thin HPFRC slabs pre-cracked at different crack opening displacement values and subjected to varying load levels (Fig. 3). The study revealed

that pre-cracking stages and load levels significantly affect cyclic creep and fatigue performance. Additionally, a particular focus was placed on the evolution of damage under cyclic loads and X-ray imaging was employed to analyse fiber orientation, elucidating its role in governing mechanical performance variability. Numerical analyses were also performed to calibrate tensile constitutive laws, offering a simplified approach to model the bending behaviour of HPFRC and UHPC elements. Furthermore, considerations regarding the design of structural behaviour and the size effect were addressed. The findings of this thesis enhance understanding of the mechanical performance of HPFRC and

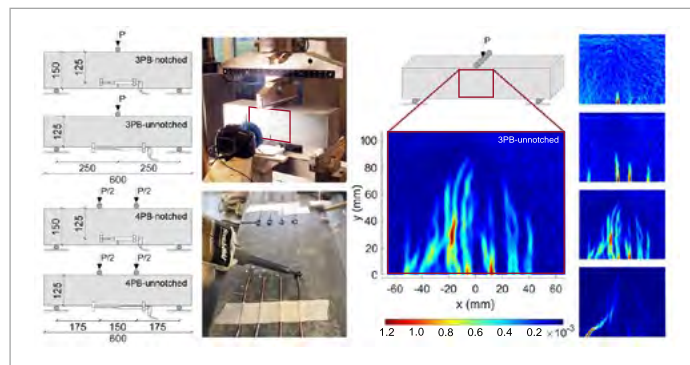


Fig. 1 - Details of the experimental campaign aimed at characterizing UHPC, including the characterization tests, their preparation, and key results highlighting the multi-cracking phenomenon.

UHPC, offering insights that support their effective application in non-structural cladding systems. By addressing tensile characterization, size effects, and cyclic behaviour, this research contributes to the development of design methodologies that ensure the

safety and efficiency of these materials in construction.

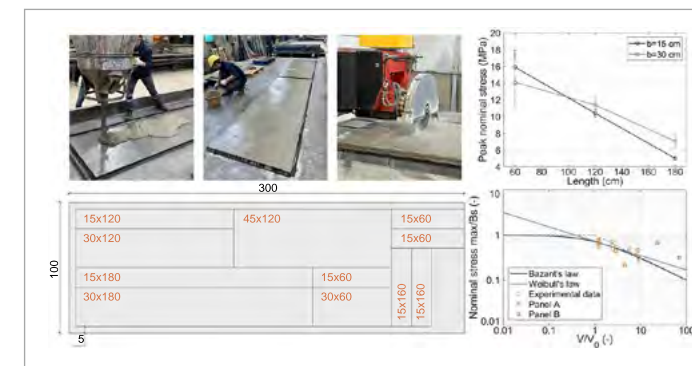


Fig. 2 - Details of the experimental campaign aimed at studying size effect, including the key results highlighting the decrease in nominal stress peak as the sample length increases and the comparison with the Bazant and Weibull laws.

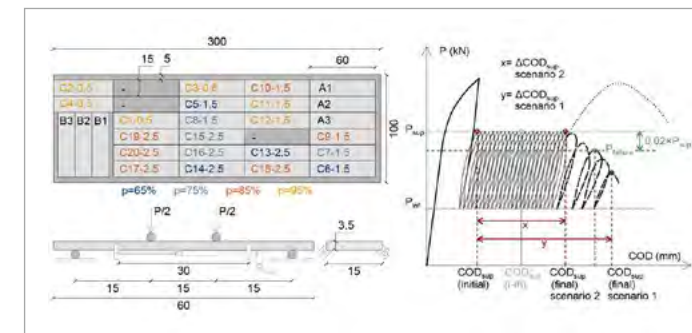


Fig. 3 - Details of the experimental campaign aimed at studying cyclic behaviour, including sample preparation, test setup, and testing procedure.

BRIDGING THE GAP BETWEEN RESEARCH AND INDUSTRIAL PRACTICE WITHIN A MULTI-RISK FRAMEWORK FOR EARTHQUAKE-TRIGGERED NATECH

Angela Chiecchio - Supervisor: Roberto Paolucci

Natech consist in technological accidents which occur at major-risk industrial plants when triggered by several natural hazards (among the others, earthquakes, floods, lightning). Common consequences include large environmental, economical, and social impact to human health and the surrounding environment. These events are however nowadays poorly studied, especially because of their multi-disciplinary and cross-cutting aspects which space between different sectors, such as: (1) the definition of the hazard at the site with its related uncertainties, (2) the characterization of the vulnerability of the interconnected elements of the system, together with the uncertainties of such definition, and the (3) analysis of the expected consequences, usually represented in terms of fires arising at the establishment. Some contributions in terms of Natech studies have been given in the last decades, but many challenges are still present, especially when transposing Natech risk assessment into practice.

In this context, this PhD thesis, by benefitting of a strong cooperation with the industrial experts of RINA Consulting S.p.A., aims at devising a

comprehensive quantitative and innovative framework which defines the risk of Natech events at major-risk industrial plants (Fig. 1). By encompassing all the cross-sectoral aspects of such events for a realistic case study of LNG industrial plant, this thesis makes a first step towards a bridge between research and industrial practice in the framework of earthquake-triggered Natech, passing from a qualitative into a quantitative assessment and being able to integrate, inside a safety report, conventional and seismic-induced Natech scenarios, with the final objective of providing harmonized guidelines to properly study Natech within industrial applications.

Different assumptions in terms of hazard and vulnerability (such as practice-oriented simplifications to interpolate the seismic hazard curve, or possible definitions of the vulnerability through fragility curves of literature) have been tested, with the final objective of understanding how these assumptions may influence the final results. Note that for the purpose of applicability, a specific realistic case study of a Liquefied Natural Gas (LNG) plant has been designed with RINA experts to serve for the reception of LNG, the subsequent storage in cryogenic tanks, the consequent distribution by road, and the possible regasification and connection to low and high pressure systems. The designed

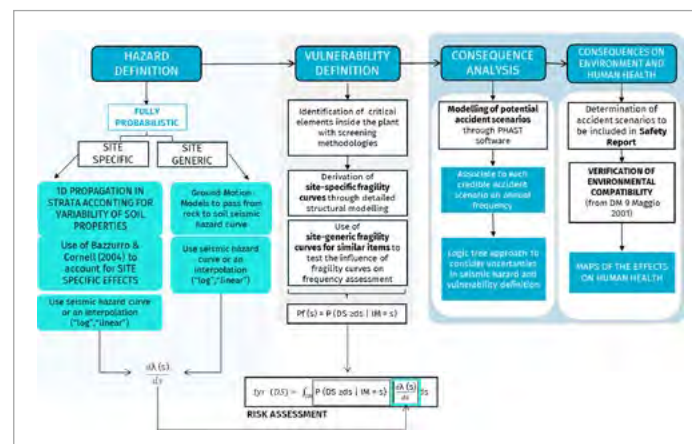


Fig. 1 - Fully probabilistic framework created in this PhD thesis for a quantitative evaluation of Natech risk inside a LNG plant located at a medium-to-high seismic hazard site and a low hazard site.

plant has been located at two different sites: a medium-to-high hazard site located in Italy (denoted as site N), and a low-hazard site located in France (recalled as site M) and the proposed framework has been applied to this establishment, with specific considerations on both a new and an existing plant. Results have demonstrated that linear interpolations of the seismic hazard curve, as well as fragility curves taken from literature strongly overestimate the corresponding risk, suggesting the need of creating ad-hoc fragility curves for the most critical elements of a LNG plant (Fig. 2). Furthermore, results have shown that most of the

computed frequencies of the accident scenarios were beyond the frequency threshold which discriminated unlikely to likely events, suggesting that Natech may have to be included in Safety Reports calculations not just in regions at high seismic risk, but also in regions at low-to-medium risk, highlighting once again the need for quantitative Natech risk assessment methodologies that could be applied in a near-future inside an industrial framework.

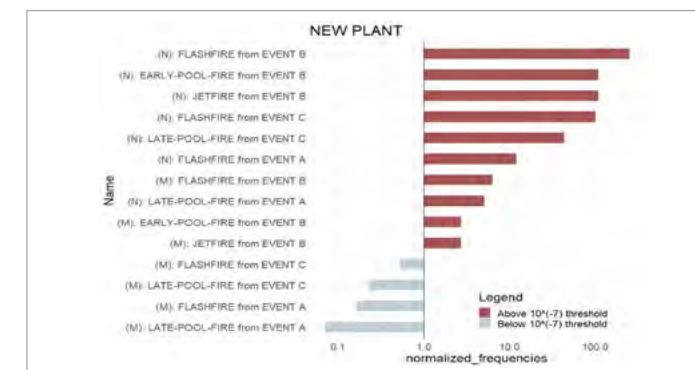


Fig. 2 - Annual frequencies of occurrence of the resulting accident scenarios computed in terms of fires evolving inside a LNG plant. All frequencies have been normalized to a 10⁻⁷ threshold, commonly introduced in this context to discriminate between the most likely and the less likely resulting scenarios. Red bars show accident scenarios which must be included inside a safety report of a critical new industrial plant

DATA-DRIVEN REDUCED-ORDER MODELING OF NONLINEAR DYNAMICAL SYSTEMS

Paolo Conti – Supervisor: Attilio Frangi

Co-Supervisor: Andrea Manzoni

The simulation of complex phenomena in science and engineering typically requires solving computationally expensive, high-dimensional, parameterized, nonlinear systems of partial differential equations (PDEs). To mitigate these challenges, reduced-order models (ROMs) have been developed to accelerate computations while maintaining a desired level of accuracy. However, many modern applications face situations where the governing equations are unknown or partially known, or access to full-order solvers is limited. This has led to the development of data-driven techniques that construct ROMs directly from data measurements of the system. Nevertheless, these ROMs often suffer from lack of interpretability and reliability due to the absence of incorporated physical insights.

In this thesis, we develop machine learning methods for constructing ROMs for nonlinear dynamical systems in a data-driven manner while non-intrusively extracting and exploiting physical knowledge. This hybrid approach aims to retain the flexibility, adaptability, and generality of non-intrusive methods while ensuring

the accuracy, extrapolation capability, and predictive power of physics-based methods. Our approach consists of two main strategies. On one hand, we learn reduced-order dynamical models by simultaneously discovering reduced-state variables and their governing dynamics. By learning governing equations in the form of ROMs, these methods emerge as promising candidates to accelerate scientific discovery in fields where such equations are yet to be uncovered, such as in neuroscience and climate modeling. On the other hand, we employ multi-fidelity surrogate modeling techniques to leverage information from multiple datasets at different levels of accuracy and costs, thereby enhancing the performance of single-fidelity ROMs.

These approaches enhance the interpretability and reliability of the ROMs, enabling accurate

parametric generalization and temporal forecasting. The common building block for all the proposed techniques is neural networks, whose flexibility allows for the potential integration of the two approaches into a unified framework, laying the foundation for a new generation of data-driven ROMs. Thanks to the versatility and generality of these methods, we derive efficient ROMs for nonlinear dynamical systems across a wide range of applications, including the dynamics of Micro Electro-Mechanical Systems (MEMS) in structural mechanics, the motion of unsteady flows in fluid dynamics, the propagation of electrical signals in computational biology, and more.



Fig. 1

UAV MONITORING OF DAM JOINTS: A FEASIBILITY STUDY

Mohammad Hajjar – Supervisors :Gabriella Bolzon, Emanuele Zappa

A substantial number of existing dams were built several decades ago, making them vulnerable to aging and deterioration. These critical infrastructures require continuous monitoring to ensure their safety for future use. Typically, displacements are measured using sensors installed directly on the structure, providing localized point-wise data. However, not all dams are equipped with such systems, and essential information for an effective structural health monitoring may be lacking. Alternatively, optical sensors mounted on drones can be used to scan the surface and obtain the requisite measurements. This PhD thesis studies the feasibility of applying vision-based techniques as monitoring tools for measuring relative displacements at joints in dams. The techniques applied are the following: Three-Dimensional Digital Image Correlation (3D DIC), Time-of-Flight (ToF), and photogrammetry. Each of these techniques has limitations when utilized in uncontrolled circumstances, leading to reduced accuracy. Indoor and outdoor experimental works are conducted under diverse environmental conditions, to recreate a real field monitoring. 3D DIC is initially used to monitor

relative displacements due to fracture propagation in prestressed concrete samples tested in the laboratory, in the presence of multiple cracks. The crack profiles along the specimen height are obtained, where the smallest detected crack is around 0.02 mm. This experimental data is employed in an inverse analysis procedure to determine the fracture properties of concrete. A reduced Finite Element (FE) model is proposed, where the discretized domain focuses on a single crack and the information collected by DIC is also used to define the boundary conditions. This process is similar to that potentially utilized to characterize joints in dams. Then, an outdoor test is conducted with partial shadows intentionally applied to the monitored region, in order to examine the effect of uneven illumination on 3D DIC measurements. Compensation techniques, involving image brightness adjustment, are proposed to mitigate this effect. The mean error and its standard deviation are adopted as evaluation metrics to evaluate the quality of the DIC data. The presence of shadows caused disturbances, resulting in fluctuations of the measurements around the mean value. The brightness adjustment

methods moderately decrease the standard deviation. Moreover, it was found that enhancing the brightness of the reference image is necessary only if it contains a shadow. In the final experiment, the three vision-based techniques (3D DIC, ToF, and photogrammetry) are used to measure the relative displacements between two large concrete blocks. The experimental setup, including outdoor conditions, specimen roughness, and size, closely mirrors field measurement conditions in dams. Post-processing practices are implemented to enhance the measurement precision, and a general evaluation of the performance of each technique is conducted. A small drone is used for photogrammetry-based image acquisition, while the ToF device and the cameras used for DIC are mounted on stable supports. However, the proposed displacement calculation methodology accommodates for variations in the ToF device location between scans. The results show that 3D DIC is the most robust methodology, with small fluctuations observed in the measurements of the other two techniques. Photogrammetry demonstrated superior accuracy compared to ToF, with its

measurements differing from those obtained by DIC by no more than 0.52 mm. In general, ToF devices do not capture in-plane dimensions. This limitation can be overcome by employing the data from the captured color image. A technique is developed which detects a feature in the color image, and then determines its corresponding location in the 3D point cloud. Despite the low resolution of the depth camera, promising results are achieved with a maximum error of 0.64 mm for in-plane measurements. The maximum error for out-of-plane displacements is 2.88 mm, which reduces to 1 mm after excluding outliers. In terms of payload, photogrammetry is the most flexible technique since it only requires a single camera mounted on a drone. 3D DIC needs a larger drone to carry and operate two cameras simultaneously. For ToF recordings, a medium-sized drone equipped with an onboard computer can be used. Future improvements in depth camera resolution will significantly enhance measurement accuracy. Overall, this study demonstrates the feasibility of using optical sensors mounted on drones to measure displacements in dams, while providing solutions to address some current challenges.

GRADED AND TOPOLOGICAL MECHANICS FOR ELASTIC WAVE MANIPULATION

Luca Iorio - Supervisor: Raffaele Ardito

Co-Supervisors: Stefano Gonella, Jacopo Maria De Ponti

The field of metamaterials – engineered materials exhibiting dynamic or static behaviours with properties surpassing those of their constituent components – has reached a significant level of maturity. The objective of this thesis is to investigate and design metamaterials that facilitate the localization of wave and elastic energy in both space and time. This research delves into the advancement of wave manipulation through the use of graded and topological metamaterials. It introduces and evaluates novel optimization techniques for achieving optimal grading, thereby enabling superior control over wave dynamics. Furthermore, the study examines the emergence of non-locality effects without requiring explicit non-local implementations, utilizing modal coupling and grading to enhance wave energy localization across spatial and temporal domains. Subsequently, the focus shifts to the realm of topology, encompassing a spectrum of phenomena from dynamic to static topological effects. The work provides theoretical advancements in directly designing topological features, with a particular emphasis on Kagome lattices. The final section explores the application of topological

principles in the development of radiofrequency mechanical devices, offering practical insights into their implementation. In summary, this thesis consolidates novel methodologies and prototypes within the domain of dynamic and static metamaterials. It highlights their potential for industrial and technological applications, thus bridging the gap between fundamental research and practical implementation.

A WORKFLOW FOR ARCHITECTURAL AND STRUCTURAL EARLY DESIGN OF TALL BUILDINGS WITH OUTER DIAGRIDS THROUGH AI-DRIVEN AND COMPUTATIONAL DESIGN STRATEGIES

Seyedpooyan Kazemisangedehi

Supervisors: Aldo Ghisi, Alireza Entezami, Michela Turrin

This dissertation presents an innovative framework that integrates artificial intelligence (AI), specifically automation and machine learning (ML), into the architectural and structural early design of tall buildings with outer diagrids, focusing on seismic resilience. At the core of this research is developing an AI-enhanced methodology that encapsulates computational design, structural engineering, and advanced ML tools, including creating and validating surrogate models for efficient seismic response prediction.

A key advancement is the automated workflow that synergizes various software tools—Rhinoceros 3D for architectural modeling, Grasshopper for parametric design, Karamba 3D and OpenSees for structural analysis, and Python scripts for simulation automation—culminating in a seamless, integrated design process. This workflow is further enhanced by leveraging high-performance computing, significantly accelerating the simulation of seismic responses across multiple design iterations. This research also investigates the interplay between architectural parameters (input features) and structural performance metrics (responses

to seismic events) through techniques like feature selection (to find the most important parameters). This work emphasizes surrogate modeling, utilizing both classical ML and deep learning techniques, to overcome the computational burden of traditional finite element analysis, offering substantial efficiency without sacrificing accuracy. Surrogate models are trained based on input features and responses, providing a deeper understanding of how design decisions impact seismic resilience. Through meticulous case studies, the framework's practicality is demonstrated, showcasing its ability to harmonize architectural

aesthetics with structural integrity under seismic forces. This dissertation contributes an innovative approach to tall building design, underscoring the transformative potential of AI in facilitating informed, resilient, and efficient architectural and structural solutions from the conceptual stage. By highlighting the integration of AI through automation and ML-based surrogate modeling, this work paves the way for future advancements in the field.

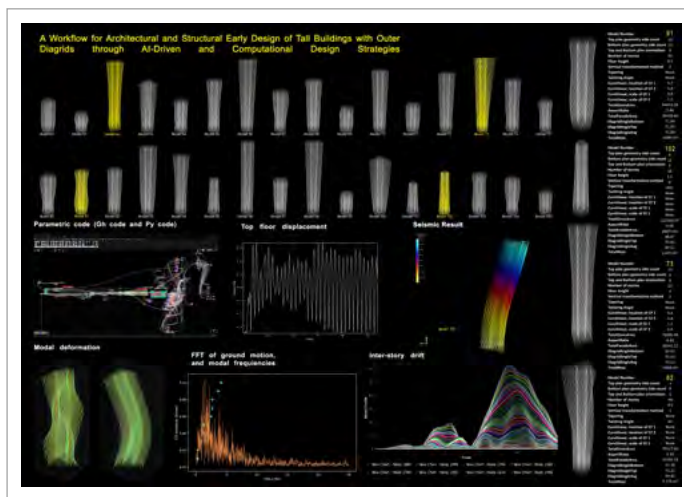


Fig. 1 - An overview of the whole procedure of research

DEVELOPMENT OF MODELS FOR THE SIMULATION OF THE MECHANICAL BEHAVIOR OF CORDS USED IN TIRES

Lucas Pires da Costa – Supervisors: Claudia Comi, Giorgio Novati

Polymeric twisted yarns and cords serve as essential reinforcements in tire structures, offering a high strength-to-weight ratio compared to metallic reinforcements. This work presents a novel macroscopic numerical model to simulate the mechanical behavior of rayon yarns and cords under different loading conditions. A comprehensive experimental campaign was conducted at Pirelli SpA and Indorama Ventures SpA laboratories to analyze the mechanical response of untwisted and twisted yarns, multi-ply cords, and dipped cords. The results were used to develop an anisotropic viscoelastic-viscoplastic constitutive model capable of capturing the key mechanical features of these reinforcements.

The geometrical model employed in this study describes the local filament orientation within single-ply and multi-ply yarns. For single yarns, fibers are assumed to follow coaxial helices with a constant pitch. For multi-ply cords, the "doubly-wound" helix theory is used, and an averaging procedure is applied to define an effective reinforcement direction at each point of the equivalent cylindrical continuum model. This approach enables a realistic representation of the

reinforcement structure and its mechanical response under different loading conditions. The constitutive model is formulated within the framework of the thermodynamics of irreversible processes. It incorporates elastic, viscoelastic, and viscoplastic contributions, accounting for both the unique geometry of the reinforcements and the non-linear dissipative behavior of rayon fibers. The elastic component is characterized by an anisotropic Helmholtz free-energy function, while the viscoelastic behavior is modeled using a transversely isotropic formulation with a single retardation time. The viscoplastic behavior is governed by a yield condition dependent on the stress along the fiber direction, ensuring accurate representation of the material response under various loading scenarios. When fibers are loaded in tension, they exhibit high stiffness due to the direct axial load transfer. However, under compression, individual filaments tend to buckle or bend, significantly reducing their load-bearing capacity. This anisotropic behavior necessitates a constitutive model capable of distinguishing between tensile and compressive states. By incorporating the piecewise linear approach, the model

effectively captures the transition between these states, ensuring a realistic representation of the reinforcement's mechanical response while preserving the overall material symmetries. To validate the numerical model, experimental tests were performed, including uniaxial tensile tests on untwisted and twisted yarns, as well as multi-ply cords. The model was calibrated using force-strain data from untwisted and twisted yarns and subsequently validated against independent experimental results. Three-point bending tests on dipped cords were also conducted to evaluate the effects of adhesive coatings on mechanical behavior. The numerical simulations demonstrated excellent

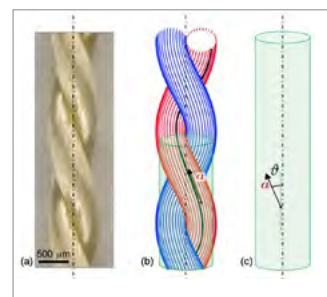


Fig. 1 - (a) Microscopic image of a 2-ply rayon cord (linear density of 1840 dtex and 480x480 twists per meter); (b) schematic view of external fibers of the two yarns in blue and red, with the definition of the fiber direction α ; (c) equivalent cylinder.

agreement with experimental results, capturing key mechanical characteristics such as the reduction in stiffness with increasing twist, non-uniform stress distribution within the reinforcement cross-section, and the gradual transition between viscoelastic and viscoplastic regimes.

An essential contribution of this study is the ability of the proposed model to estimate the local stress and strain distribution inside reinforcements, depending on the cord construction. The results provide valuable insights into

the impact of cord construction on macroscopic mechanical responses. Specifically, the study highlights:

The reduction in overall elastic stiffness with increased transversely isotropic nature of the material and the varying fiber inclination.

The heterogeneous stress distribution within twisted yarns and cords due to non-uniform fiber inclination.

The gradual transition from viscoelastic to viscoplastic regimes, driven by progressive

fiber yielding, where fibers with smaller inclination angles yield first.

The differentiation in mechanical behavior between greige and dipped rayon cords, which is attributed to the altered properties of the outer adhesive-coated layer. Adopting different elastic constants for the dipped region resulted in excellent agreement between numerical and experimental responses.

The significance of incorporating the bimodular effect to capture differences in fiber response under tension and compression, particularly in the analysis of local stresses in multi-ply cords and the global behavior of dipped cords in bending tests.

By integrating geometrical formulations, and finite element simulations, this study provides a powerful tool for optimizing reinforcement construction.

The proposed approach can be extended to other fiber-reinforced materials with similar structural characteristics, offering a broader applicability in the modeling and design of polymeric reinforcements.

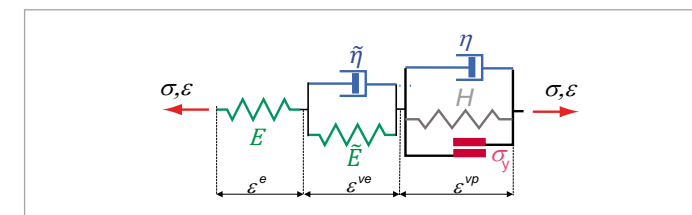


Fig. 2 - One-dimensional representation of the elasto-viscoelastic-viscoplastic model.

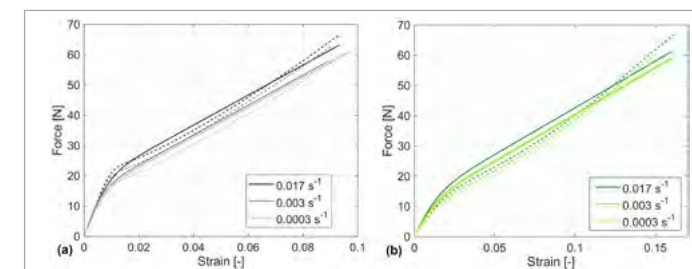


Fig. 3 - Uniaxial tensile test of single-ply yarns in humid conditions at different strain rates, comparison between experimental data (dashed lines) and numerical results (solid lines): (a) untwisted yarn; (b) yarn with 380 twists per meter.

DEEP LEARNING STRATEGIES FOR MULTISCALE MODELING AND MATERIALS DESIGN

Jose Pablo Quesada Molina – Supervisor: Stefano Mariani

This thesis investigates the potential of deep learning (DL) methodologies in materials informatics, focusing on predictive and prescriptive tasks for modeling and design. Addressing critical gaps at the intersection of materials science and DL, this work develops robust frameworks for multiscale modeling and inverse design of heterogeneous materials. These contributions are applied to polysilicon microstructures and composite materials, leveraging DL architectures to advance data-driven approaches in materials engineering.

The foundational chapters establish the theoretical and methodological context. Chapter 1 reviews literature, highlighting the main challenges in integrating DL into material modeling and design. Chapters 2 to 5 develop a theoretical framework encompassing homogenization theory, discussing analytical, numerical, and data-driven homogenization approaches, as well as the characteristics of the heterogeneous material systems under study. These discussions set the stage for the frameworks presented in Chapters 6 and 7. This dissertation explores image-driven DL strategies through two case studies: polycrystalline structures and two-phase

composites with periodic microstructures. Advanced DL architectures, including Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs), are employed for multiscale modeling and design. By distinguishing between predictive tasks (modeling material properties based on microstructural features) and prescriptive tasks (optimizing and designing materials with desired properties), this work addresses key research gaps.

In the area of predictive tasks: (i) the impact of dataset size and input granularity on model accuracy, (ii) generalization of CNN-based models across diverse microstructures, (iii) integration of CNN-based approaches into multiscale homogenization frameworks. In the prescriptive tasks: (i) influence of training data distribution on DL model extrapolation, (ii) latent-space optimization strategies for GAN-based inverse design, (iii) visualization techniques for improving interpretability of the Material Property Space (MPS). Chapter 6 addresses predictive tasks through a CNN-based multiscale modeling framework for polysilicon microstructures. A CNN was developed to predict effective elastic properties

from microstructural images, significantly improving accuracy while bypassing feature engineering. A granularity index was introduced, combining the average number of grains per Stochastic Volume Element (SVE) with image resolution to quantify structural detail. Systematic analysis of dataset size and resolution provided insights into balancing computational efficiency and accuracy. The CNN trained on an optimized dataset achieved a Mean Squared Error (MSE) of $3.16 \times 10^{-1} \text{ GPa}^2$ (RMSE: $5.62 \times 10^{-1} \text{ GPa}$), translating to < 0.5% relative error in property predictions. Generalization capabilities were tested on unseen microstructures, including artificially generated monocrystalline samples and new mesoscale configurations. The model maintained strong performance across all scenarios, achieving an R^2 value of 0.9817, demonstrating adaptability to diverse material structures. Furthermore, CNN-based predictions were integrated into a multiscale framework, seamlessly connecting microstructural properties with device-level behaviors in MEMS structures. A modular resampling approach allowed size-agnostic modeling, making it adaptable to varying

macroscopic dimensions. The CNN effectively mapped local elastic properties to the effective modulus of MEMS structures, achieving an MSE of $2.47 \times 10^{-2} \text{ GPa}^2$ (RMSE: 0.16 GPa), demonstrating robustness in out-of-distribution cases.

Chapter 7 focuses on prescriptive tasks by applying DL strategies to inverse design, targeting two-phase composite materials composed of polylactic acid (PLA) and thermoplastic polyurethane (TPU). A GAN-based generative model was combined with a CNN predictive framework to generate optimized material designs based on target effective properties. The study systematically analyzed how training data distribution impacts inter- and extrapolation capabilities, highlighting the importance of data diversity in inverse design methodologies. Latent-space optimization was enhanced using a gradient-based approach, improving inverse design performance, particularly in sparsely populated or extreme out-of-distribution (OOD) regions. Active learning (AL) and transfer learning (TL) strategies refined the process, significantly reducing design errors. A second optimization campaign reduced root sum of squares errors (RSSE) from 69.39% to 85.73% for a set of predefined critical design targets, while CNN prediction errors remained below 10% for all effective properties across these points. A statistical analysis of the minimum SSE values revealed optimal trade-offs between the

number of latent vectors and the number of optimization iterations. Beyond a threshold, additional iterations yielded diminishing improvements unless coupled with an increased number of latent vectors, emphasizing the need for an optimized search strategy for robust inverse design. Additionally, the study highlights the importance of visualization techniques to improve interpretability. By mapping spatial error distributions across the MPS and correlating factors such as training data density and CNN prediction accuracy, key insights were provided for refining model performance. While the proposed framework significantly improves inverse design efficiency, future work should refine convergence criteria, explore alternative hyperparameter tuning techniques, and integrate physics-informed learning for enhanced generalization. By combining GAN-based generative modeling with CNN-based predictive frameworks, this research presents a scalable, data-efficient approach to inverse design. The integration of active learning and transfer learning significantly enhances model reliability in OOD scenarios, addressing a major limitation in existing inverse design frameworks. The ability to optimize material configurations without exhaustive finite element simulations represents a meaningful step forward in deep learning-based material discovery. In summary, this dissertation advances DL-based modeling

and design frameworks for heterogeneous materials. Chapter 6 introduces a CNN-based multiscale modeling approach that improves predictive accuracy, generalization, and hierarchical material modeling. Chapter 7 extends DL applications to inverse design, optimizing GAN-CNN strategies for efficient material configuration generation. These contributions expand the field of materials informatics, bridging key gaps in both predictive and prescriptive tasks. By providing scalable, robust, and interpretable deep learning methodologies, this research paves the way for future advancements in multiscale modeling and material optimization.

IMPROVING DATASETS AND MODELS FOR THE ENGINEERING CHARACTERIZATION OF EARTHQUAKE GROUND MOTION IN DIVERSE SEISMICITY CONDITIONS

Fadel Ramadan – Supervisor: Chiara Smerzini

The thesis presents some advancements in the calibration of Ground Motion Models (GMMs), utilizing empirical data obtained from diverse seismic contexts with the objective to enhance predictive capabilities for GMMs for engineering applications. The study addresses three key challenges in GMMs development: (1) accounting for near-source complexities in both vertical and horizontal components, (2) developing GMMs in low-to-medium seismicity regions with limited data, and (3) Analyzing nontraditional intensity measures, such as waveform envelopes.

A novel model was developed for the amplitudes of vertical-to-horizontal (VH) ratio acceleration response spectra for shallow crustal earthquakes in Italy, using the ITA18 dataset. This GMM ensures compatibility with the model for horizontal component and includes corrections for near-source conditions based on the global near-source dataset, (NESS1.0, Pacor et al. 2018). To test adaptability to regions with low seismicity, the models for Italy were applied to Continental France, using the FR20 dataset (comprising 2,300 records

from 1996 to 2019) to verify the performance. Residual analyses highlighted the need for modifications to the distance scaling and source scaling for the horizontal component, alongside the corrections to be applied to the VH model in near-source conditions.

Moreover, insights from the recent Eastern Turkey seismic sequence contributed in the study of characteristics of the waveform envelopes using over 500 records. Following other literature studies, these envelopes were interpolated with a lognormal distribution model, and were analyzed as a function of the magnitude, site conditions, and source-to-site distance, providing useful insights for empirical modeling.

A PFEM NUMERICAL FRAMEWORK FOR SIMULATING 3D PRINTING OF ADVANCED MATERIALS

Giacomo Rizzieri – Supervisor: Massimiliano Cremonesi

Co-Supervisor: Liberato Ferrara

Additive manufacturing techniques, such as 3D printing, are nowadays well established in different industrial sectors, including automotive, aerospace, and healthcare, where they enhance production efficiency. However, their adoption in construction remains limited due to many technical challenges and uncertainties. Advances in numerical modelling are expected to partially bridge this gap, offering designers greater control and insight into the processes and materials involved in these new construction approaches.

This thesis presents an advanced numerical framework for simulating 3D printing of complex materials. Using the Particle Finite Element Method (PFEM), which combines a Lagrangian FEM formulation with a robust re-meshing algorithm, it efficiently handles large displacements, evolving domains, and automatic free-surface tracking.

Within the PFEM context, two FEM solvers were developed, utilizing implicit and explicit time integration schemes respectively. Initially validated for Newtonian fluids, the solvers were extended to handle more complex behaviours, including viscoelastic, viscoplastic, and

elasto-viscoplastic materials, potentially undergoing time-dependent evolution or fluid-to-solid phase transitions. The non-Newtonian solvers were benchmarked on well-established case studies involving free-surface flows, such as dam breaks, drop impacts, and jet buckling. At the same time, a set of specialized numerical techniques was developed to accurately simulate the 3D printing process in the PFEM framework. These tools include the use of the Arbitrary Lagrangian-Eulerian (ALE) approach to model nozzle movements, advanced algorithms to accurately capture base and interlayer contact, an adaptive mesh de-refinement technique to decrease the computational cost, and an

efficient nodal mapping scheme to transfer historical variables across re-meshing events. The overall framework was validated by reproducing the extrusion and layer-deposition phases of 3D Concrete Printing (3DCP) and comparing results with experimental data. The explicit solver proved efficient in simulating a variety of different printing scenarios, highlighting the influence of material properties (density, yield stress, viscosity) and process parameters (nozzle diameter, nozzle height, printing velocity, extrusion velocity) on the morphology of the printed layers. The outcomes of these simulations enabled the generation of a dimensionless map summarizing all possible cross-sectional shapes and printing regimes in free-flow

deposition of yield-stress fluids. Vertical and inclined multi-layer walls were also simulated and compared with experimental data from literature or provided in the framework of the collaboration with TU/e Eindhoven. Numerical results aligned closely with the measured data, also providing insights into the role of material compressibility in 3DCP. The implicit solver was preferred in all those cases involving longer printing times and where the objective was to predict in advance the geometrical conformity and buildability of complex shape objects. In the first example, a rectangular wall characterized by a W-type infill was virtually printed, investigating the role of thixotropy and assessing interlayer bonding quality at intersections. The second example involved the design and virtual printing of three parametric hollow objects, to evaluate their stability and geometrical conformity under varying material properties. This analysis also highlighted how the numerical tool can be used to predict when and where additional support could be placed to enhance the final quality of printed structural components.

Overall, the proposed framework proved to be accurate, robust, and potentially applicable to different classes of materials, such as clays and polymers. Future improvements will aim to decrease the computational cost through the integration of AI and machine learning techniques, transforming the framework into an effective predictive tool and enabling real-time optimization and the creation of reliable digital twins for the 3D printing process.

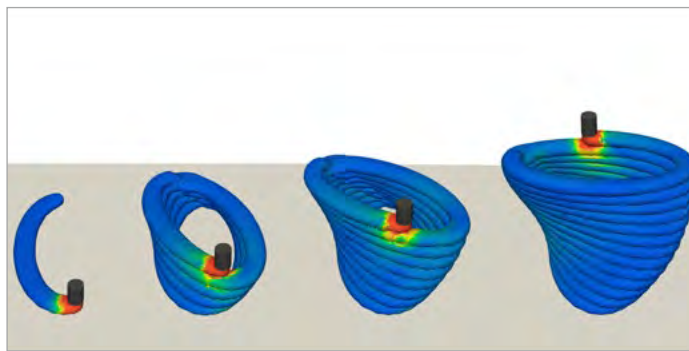


Fig. 1 - Simulating 3D printing of a complex object with a viscoplastic Bingham material.

ON THE USE OF TEXTILE WASTE FIBRES FOR SUSTAINABLE SOLUTIONS IN EARTH EMBANKMENTS REPAIR

Chiara Rossignoli - Supervisor: Donatella Sterpi

Earth embankments deteriorate due to natural aging and external actions now intensified by climate change, therefore effective repair methods are urgently needed. Common interventions aimed to restore embankments, such as the reconstruction of the damaged area or the injection of low-pressure grouts to fill fractures and burrows, may cause the weakening of the structure due to discontinuities between natural and treated zones. Moreover, since such repair techniques require huge volumes of materials, more sustainable materials are encouraged. At the same time, the textile and fashion industries are looking for sustainable waste management and disposal strategies to face environmental problems concerned with the voluminous textile waste dispatched to landfills or incinerators. The use of soil mixed with textile waste in embankment improvement has been investigated with the twofold purpose to identify an effective engineering practice and to provide a strategy for the circular economy of textiles. To conduct the research, an experimental approach was initially adopted, followed by an exploration of simple, yet functional, failure modelling to describe the behaviour of treated

soils. Laboratory tests have been conducted on soil specimens collected from the Secchia River embankment, Northern Italy, to define the appropriate mixture proportions and to compare physical properties and hydro-mechanical behaviour of natural soil and soil treated with linen and viscose fibres. The results indicate that with appropriate fibre content, manageable and homogeneous mixtures can be achieved, making this solution suitable for practical applications; however, ensuring applicability at the site scale requires the use of appropriately sized equipment. The presence of the selected textile fibres significantly impacts the hydro-mechanical behaviour of the soil by modifying its density, compressibility, strength, hydraulic conductivity, retention capability, and volumetric behaviour (i.e., shrinkage and swelling). The effect of fibres depends on their geometry, properties, and the sample preparation procedure, thus varying with different fibre configurations. In general, the presence of fibres reduces the maximum dry density achievable through compaction. However, the density of laboratory samples is also influenced by the sample preparation technique and the procedure adopted for saturation,

which leads to contrasting effects on sample compressibility. Samples reinforced with fibres of specific geometry (i.e., length and diameter) and optimal fibre contents exhibit an increased shear strength. The influence of fibres on hydraulic conductivity and water retention is primarily governed by their effect on the pore network and their hydrophilic nature. Moreover, the presence of fibres reduces soil swelling during saturation and shrinkage during drying, making them suitable for limiting crack formation in earth embankments due to drying-wetting cycles. The obtained results highlight the importance of considering the relative size between fibres and soil particles and the scale effect for specific applications. As the results demonstrate that the geotechnical properties of the treated soil can be engineered to meet specific site requirements, the proposed approach seems a promising solution for earth works and ground improvement, such as embankment repair and restoration.

FROM THE FAULT RUPTURE TO CITY SEISMIC RESPONSE: 3D MULTI-SCALE PHYSICS-BASED SCENARIOS OF EARTHQUAKE EFFECTS

Srihari Sangaraju - Supervisor: Roberto Paolucci

Co-Supervisor: Fabian Bonilla

With the growing accessibility of high-performance computing (HPC), 3D physics-based simulations (3D PBS) have become a standard tool for simulating earthquake ground motions. While the spatial extent of regions modelled in 3D PBS is expanding, small-scale features such as highly heterogeneous and/or non-linear soft sediments as well as the built environment in urban areas are often simplified or omitted altogether. This is largely due to the exponential computational overhead required for their accurate representation, but also to the complexity in getting a detailed level of information in large areas. However, the localised effects of these features on ground motions are well-documented in smaller-scale simulations. For instance, detailed site response analyses routinely incorporate realistic nonlinear constitutive models in 1D and 2D, while soil-structure interaction (SSI) studies examine the influence of building response on ground motions in small domains. However, these effects remain underexplored at urban scales (Site-City Interaction, SCI), where they are likely to be more pronounced.

In this context, the primary objective of this work is to

advance the state-of-the-art in 3D PBS by enabling the simulation of realistic ground motions in large urban areas while maintaining computational efficiency. The key contributions of this research mostly include (1) the progress on validated case studies of simulated ground motions in urban areas, (2) the development and implementation of advanced numerical tools within the high-performance spectral element code SPEED (<https://speed.mox.polimi.it/>) developed at Politecnico di Milano, (3) the incorporation of realistic nonlinear soil behaviour and (4) the implementation of the module SPEED-SCI for coupling of simple nonlinear building models in 3D PBS to analyse SCI effects.

Nonlinear soil behaviour is modelled by extending Iwan's

multi-surface plasticity approach from 1D to 3D. This method discretises the nonlinear stress-strain curve of soil into linear segments, effectively eliminating the need for computationally intensive Newton-Raphson iterations. In SPEED-SCI, buildings are simplified as nonlinear multiple degree-of-freedom (MDOF) shear systems. Base reaction forces from buildings are applied as point forces on the ground surface, while the buildings are subjected to ground accelerations at each time iteration. This approach avoids the need for mesh refinement and eliminates additional computational overhead. A pre-processing tool is also developed to calibrate nonlinear structural parameters from simple building inventory data, streamlining the workflow

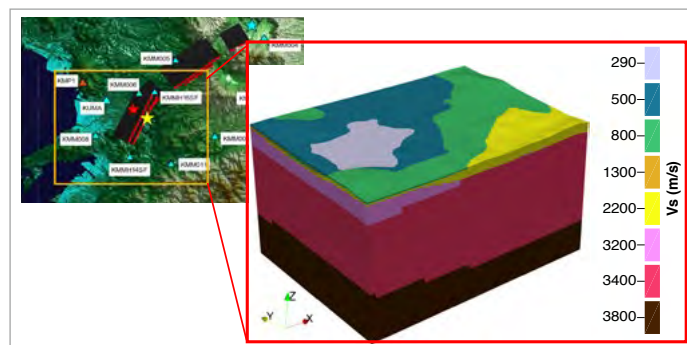


Fig. 1 - Large-scale 3D nonlinear ground motion simulation of Mw 6.1 Kumamoto earthquake: 3D Numerical model.

and enhancing usability.

Validation of 3D PBS was performed within a Blind Prediction exercise, organized within the Effects of Surface Geology (ESG6) conference, simulating broadband ground motions from weak and strong events of the 2016 Kumamoto earthquake sequence. The region's highly heterogeneous subsurface model and complex finite-fault seismic source presented significant challenges. The SPEED workflow is updated to account for these complexities. The 3D PBS (visco-elastic) were first performed by omitting the thin heterogeneous sediments to generate the low-frequency ground motions, which were then enriched with high frequencies using a routine based on artificial neural networks (ANN2BB). A

subsequent 1D site response analysis was carried out to include the seismic response of the shallow sediments down to about 50 m depth. While these simulations are not fully coupled, they satisfactorily reproduced recorded ground motions, demonstrating the efficiency of the 3D PBS and ANN2BB approaches.

The Kumamoto region model was further refined to include highly heterogeneous soft sediments, enabling fully coupled nonlinear simulations employing the nonlinear model developed in this work. These simulations were stable and required only twice the computational time of viscoelastic simulations. Results indicated that while shear modulus degradation is concentrated at the basin edge

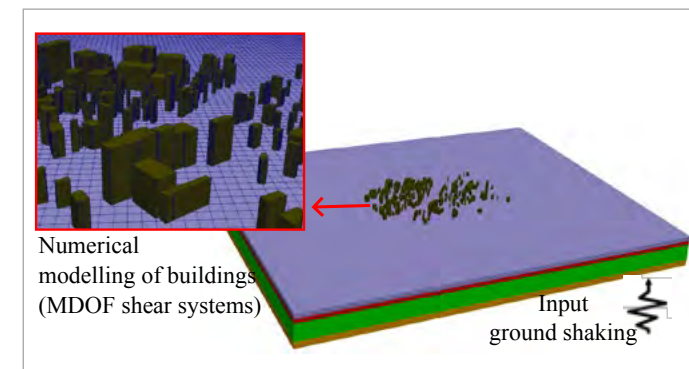


Fig. 2 - Coupling of building response with ground motions at urban-scale.

near the seismic source, long-period ground motions are deamplified on the other side of basin, as they traversed the basin.

The accuracy and stability of the SPEED-SCI implementation was validated against CAMUS-III shake table experimental data. Further, its practicality was demonstrated through a 3D plane wave simulation of the Kumamoto region incorporating a cluster of 298 tall buildings in the city centre. Observed amplification and deamplification of ground motions near buildings were consistent with previous studies, though the spatial variation is case-dependent for this configuration of buildings. In conclusion, this work provides the computationally efficient numerical tools for performing fully coupled earthquake ground motion simulations, capturing wave propagation from the earthquake fault to structures. While fully coupled fault-to-structure simulations were not yet performed in this work, all necessary components are developed, and validated, which can be exploited in immediate future.

MODEL-BASED AND DATA-DRIVEN METHODOLOGIES TOWARD PREDICTIVE DIGITAL TWINS OF STRUCTURES

Matteo Torzoni – Supervisor: Stefano Mariani

Co-Supervisor: Andrea Manzoni

The digital twin concept has emerged as a paradigm to enable diagnostic and predictive capabilities that are not achievable with computational models alone. A digital twin is a personalized virtual representation of a physical asset that evolves over time. It relies on a set of computational models that are dynamically updated to persistently mirror the physical counterpart throughout its life cycle. Additionally, it features predictive capabilities that inform decisions tailored to realize value in the physical setting of interest. A bi-directional interaction between the physical and virtual domains, comprising either automated or human-in-the-loop feedback flows, is a critical enabler for digital twins. Enhanced computational efficiency is also required to handle the continuous assimilation of noisy and big data, as well as to quantify and propagate relevant uncertainties. This Thesis aims to advance digital twin technologies for monitoring the structural integrity of engineering systems by hybridizing physics-based modeling with artificial intelligence. Enabling a digital

twin perspective for critical structural systems, whether for safety or operational reasons, can unlock the potential of condition-based and predictive maintenance practices, yielding numerous benefits throughout their life cycle. We begin by laying down a theoretical groundwork and integrating cutting-edge insights from data science and engineering. This encompasses: (i) model-based and data-driven approaches to parameter identification; (ii) full and reduced-order computational models in structural dynamics to formulate damage identification strategies within the simulation-based paradigm of structural health monitoring; and (iii) machine learning techniques to extract information from sensor data, forecast future system responses, and determine optimal courses of action. Subsequently, we propose four contributions that combine simulation-based supervision, essential for addressing the lack of experimental data related to damage onset and propagation, with learnable mappings aimed at assimilating vibration recordings, enhancing damage identification capabilities, and improving computational efficiency.

Firstly, we introduce a data-driven diagnostic framework that leverages deep metric learning to map raw sensor recordings onto a damage-sensitive low-dimensional space. We investigate its ability to locate damage by exploring different training options within a Siamese architecture, demonstrating remarkable accuracy and robustness against variations in the extent and severity of damage. Secondly, we tackle the computational efficiency of surrogate models for structural health monitoring. We employ both full and reduced-order physics-based models to sequentially train surrogate components with increasing levels of approximation. The resulting multi-fidelity surrogates serve both model-updating purposes and the generation of large datasets, demonstrating superior accuracy compared to single-fidelity approximations without increasing computational costs. As a third contribution, we present a hybrid data/model approach for real-time damage identification, enhancing Bayesian model updating through learnable mappings. Damage-sensitive features are extracted from sensor

recordings via deep metric learning, and then exploited within a Markov chain Monte Carlo sampler to assess damage with quantified uncertainty. The achieved estimation accuracy and computational efficiency overcome limitations linked to the slow convergence of sampling algorithms and the curse of dimensionality affecting the inference of low-sensitivity damage parameters. Finally, we propose a digital twin framework relying on a probabilistic graphical model to encode the asset-twin interaction via observational data and control inputs. The decision-making capabilities of health-aware digital twins are assessed through demonstrations of data-driven health monitoring, prediction, and planning. While experimental data are not used, all methodologies are assessed across various case studies using noisy synthetic measurements.