MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2023

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
Prof. Stefano Mariani

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 hystorical 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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DURABILITY-BASED DESIGN OF ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC) STRUCTURES: FROM MICRO MATERIALS TO STRUCTURAL SCALE

Al-Obaidi Salam Maytham Jaber - Supervisor: Prof. Liberato Ferrara

The concept and use of Ultra-High-Performance Concrete, UHPC, can bring several advantages in terms of strength and durability aspects over the conventional concrete materials in the concrete construction industry, mainly regarding infrastructure applications.
As a matter of fact, the use of conventional materials requires cost and labor efforts for assembling the reinforcing bars, and maintenance and repair actions are demanded throughout the structure service life as a result of a somewhat unavoidable, though slow, deterioration of the structural performance.
These problems could be successfully tackled by adopting high-performance concrete materials in infrastructure applications, particularly those that are exposed to aggressive environmental exposure and structural service scenarios.
Nonetheless, the peculiarities brought by advanced materials and, in detail, the enhancement inborn in UHPC, for instance, the impressive residual tensile capacity, high compressive strength, and significant durability improvement in uncracked, and cracked states, trigger the need for formulating and validating new design procedures and methodologies. As expectable, the lack of understanding and dealing with these materials has delayed so far, their extensive implementation in a wide ray of infrastructure applications. Therefore, this study, through extensive experimental and theoretical investigations, aims to bring a contribution to consistently foster the use of UHPC materials, especially to structures exposed to extremely aggressive conditions. To obtain a rational comprehension of the UHPC materials, multi-scale level tests have been carried out with a focus on "structural durability" aspects, which meant the capacity of the material to maintain the required level of structural performance over time under the intended service conditions, including environmental exposure and expected cracking state.
Experimental tests at different scales have been used to fulfill the objectives of the thesis: micro-scale to test the micromechanical performance of steel fiber-UHPC matrix interface, mesoscale tests to study the damage-healing mechanism in small thin beams, large-scale tests to study the flexural performance of UHPC panels and model the structural durability performance, and finally full-scale structural level tests to monitor the serviceability requirements of a pilot UHPC structure.
The microscale level consists of single steel fiber pullout tests. Performed on 20mm long steel fiber embedded inside UHPC matrix with different nano-additions mix-designs. The samples were cured in tap water and 3.5% NaCl aqueous solution to understand the influence of the curing conditions on the micromechanical behavior.
Upon one month curing period, some samples were tested with a direct pullout test to represent the reference case, whereas for other samples, fibers were pulled out partially to induce some damage on the fiber-matrix interface and then immersed either in tap water or 3.5% NaCl aqueous solution for another one month to investigate the healing and deterioration mechanisms respectively. Scanning Electron Microscopy, SEM, and Energy-Dispersive Spectroscopy, EDS was conducted on the steel fiber surface and attached healing/corrosion particles to understand the nature of the occurred processes, before being tested to complete pull-out failure to assess the effects of the same phenomena on the fiber-matrix bond.

The mesoscale level involves an extensive experimental campaign on UHPC thin beams that have cross-sectional dimensions of 100mm × 30mm and length of 500mm. Durability and strength tests have been carried out on these beams via nondestructive and destructive measurements.
In order to depict the real case condition, the beams have been placed under sustained loading conditions, where a suitable loading setup was introduced and applied to the beams. Beams from different UHPC mixes, incorporating different nano- and micro-functionalized constituents were first nondestructively surveyed to quantify their steel fiber contents, and further still nondestructively tested to evaluate their stiffness via resonant vibration test and ultra-sonic pulse velocity (UPV) tests. The beams were then cracked to 200μm crack opening displacement (COD) on 150mm tensile range length and thereafter subjected to sustained flexural stress to the same level of pre-cracking load and immersed in water to simulate three different scenarios: tap water, 3.5%NaCl aqueous solution and geothermal water, obtained from a geothermal power plant located in Tuscany. The specimens stayed in the exposure baths for up to 12 months. Every three months, specimens from different materials and exposure types were tested, firstly via the same nondestructive tests as above, visually acquiring crack width imaged, UPV, and RF tests; then half of the specimens were tested in 4pbt, while the other half was tested in direct tension. From these tests, the evolution of the tensile constitutive laws was evaluated for up to 12 months of exposure and then extrapolated to be used in design approaches that can integrate and upgrade the durability performance from materials to the structural level.

The Macro scale level included tests on UHPC panels of different sizes, representative of different structural schemes, that were also subjected to pre-cracking, exposure for up to 6 months to different scenarios, and final failure tests. A yield line approach was used to predict the performance of the UHPC slabs, also employing the constitutive tensile relationships identified from the previously described tests. These UHPC panels were meant to replicate at a lab scale a real structural application, assumed as a benchmark reference in this study: a basin to collect the geothermal water located in a geothermal power plant that is in Tuscany, Italy.
The basin consists of three compartments, each one having a different material or structural scheme. The first compartment is 7.0m wide, 7.5m long, and 1.5m high and is made of a 100 mm thick ordinary reinforced concrete wall. The second compartment has the same plan and height dimensions but is made of 60 mm thick UHPC walls. The last compartment consists of 30 mm thick UHPC panels (1.4m × 1.5m) stiffened by 200mm×200mm UHPC columns. The service height level of the geothermal water is assumed equal to 1.3m.
Upon the completion of the basin and entering its service condition, several monitoring and validation tests have been carried out including steel fiber survey and loading/unloading tests with measurements of wall displacements, strains in concrete and steel bars, and crack width monitoring. These measurements were aimed to verify the design concept and evaluate the durability criteria at specific time periods.
The same monitoring and validation tests were conducted on the lab scales specimens to mimic the behavior of the second and the third compartments.

The whole experimental campaign serves as a solid background for the formulation and validation of a durability performance-based design approach for UHPC structures, which constitutes the second part of this study.
The proposed methodology encompasses the conventional structural design procedures, integrated with the material performance derived from the experiments as a function of exposure condition and time.
Moreover, such approach allows to rationally predict the service life of UHPC structures, since the serviceability and strength limit states are checked and compared to the performance and resistance capacity respectively.

LIFE-CYCLE STRUCTURAL PERFORMANCE OF RC/PC BRIDGES: COMPUTATIONAL MODELING AND EXPERIMENTAL VALIDATION

Mattia Anghileri – Supervisor: Prof. Fabio Biondini

Safe, reliable, robust, and sustainable bridges and infrastructure systems are the backbone of modern society and they serve as the basis of economic growth and sustainable development of countries.
Bridge design has provided the opportunity for some of the most challenging and creative applications of structural engineering. It is therefore a priority to protect, maintain, and manage aging bridges over the entire life-cycle. Concrete is a durable material capable of withstanding a wide range of severe environments. However, news and studies in recent years spotlighted the detrimental impact of aging and deterioration processes on infrastructure systems, particularly on reinforced concrete (RC) and prestressed concrete (PC) bridges.
Aging and deterioration effects, combined with a low durability of materials and lack of proper maintenance and repair activities, can drastically affect the bridge bearing capacity to service loads. This represents an urgent and high relevant problem, particularly in Italy where concrete bridges and infrastructure facilities built over the past 50 years are rapidly approaching the end of the service life and some of them are in a state of severe deterioration. Moreover, the traffic loading conditions considered at the design stage, including heavy vehicles, are nowadays a low estimate of the actual in-service loads. This critical situation is made more evident by recent bridge and viaduct collapse events that have occurred with alarming frequency, highlighting the importance of planning inspection, maintenance, and repair activities over the structural lifetime. The continuously increasing traffic demand, the long-term exposure to aggressive environments, and the use of new construction materials and technologies, led to the development and extensive application of a life-cycle approach that is now becoming a driving prospective in structural engineering to properly modeling and assess the residual performance of bridges accounting for the effects of deterioration processes, time-variant loadings, and maintenance and repair interventions under aleatory and epistemic uncertainties.
The thesis presents a life-cycle probabilistic framework for structural performance assessment of RC/PC bridges exposed to aging and deterioration, with emphasis on corrosion. The diffusion process in concrete members of aggressive agents, such as chlorides, is solved numerically through Cellular Automata evolutionary algorithms. Proper damage functions are adopted to model corrosion at the material level accounting for the degradation of both steel and concrete. Uncertainties are accounted for based on probabilistic methods and implemented by means of numerical simulation techniques, including Monte Carlo simulation and Subset simulation method. The beneficial effects of new data and information gathered from visual inspection, diagnostics, maintenance, and repair activities for the update of life-cycle structural assessment, are investigated with the use of Bayesian statistical inference.
The time-variant structural performance of RC/PC structures is evaluated through nonlinear analysis by means of the formulation of a deteriorating RC/PC beam finite element model which accounts for geometrical and material nonlinearities and corrosion damage. Moreover, a bidimensional modeling for plane-stress nonlinear analysis of RC/PC structures under corrosion, formulated in accordance with the Modified Compression Field Theory, is adopted to account for shear effects and local stress-diffusion phenomena. The framework is validated through the results of experimental tests available in literature on RC/PC beams, as well as collected from an extensive experimental campaign within the BRIDGE|50 research project (bridge50.org) devoted to investigate the residual structural performance of a decommissioned 50-year-old PC bridge (Figure 1). The proposed approach is applied to the life-cycle assessment of existing RC/PC bridges under corrosion, including the effects of diagnostic activities. The results of the applications highlight the effectiveness and the importance of the proposed framework for life-cycle residual performance assessment of deteriorating bridges. The thesis contributions and results are expected to provide knowledge advances for authorities managing bridges and key information to improve existing methods for safety, reliability, and residual lifetime assessment of structures and infrastructure facilities.

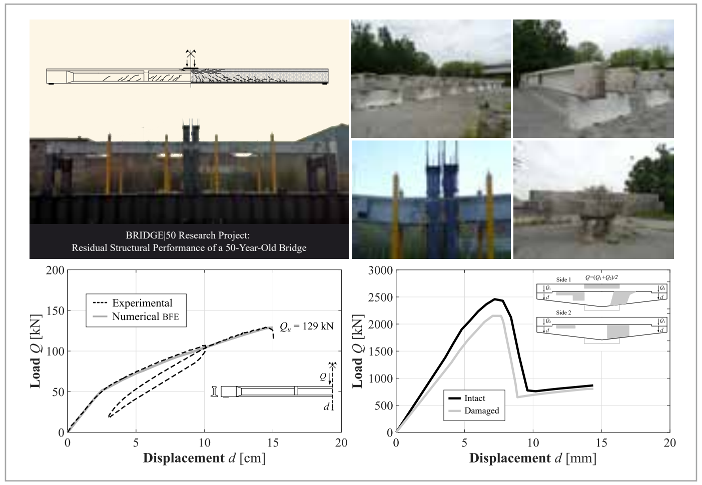

Fig. 1 - BRIDGE|50 research project (bridge50.org).

COMPUTATIONAL MODELLING OF AGEING, HEALING AND DEGRADATION OF ORDINARY AND ULTRA HIGH PERFORMANCE CONCRETE

Antonio Cibelli - Supervisors: Prof. Giovanni Di Luzio, Prof. Liberato Ferrara

"*We know that our shared planet is changing for the worse. We can seize the enormous opportunities for green growth, for good green jobs, for cheaper, cleaner power. But we need to hit the ground running to develop the solutions that we need.*" With these words Hon Alok Sharma, as new President, opened the 26th United Nations Climate Change Conference.

Concrete is the most used among the construction materials worldwide, with an estimated yearly consumption approaching 30 billion tonnes, and a demand steeply growing year by year. Although the recent efforts towards finding reliable alternatives, cement is still essential for the concrete production. Precisely the use of cement is responsible of the huge carbon footprint associated to concrete: at least 8% of global emissions caused by humankind comes from the cement industry alone. Therefore, a more sustainable economy cannot disregard a substantial re-thinking of the cement-based materials usage.

A case history analysis provided by the CON-REP-NET project in 2007 showed that 50% of the repaired concrete structures failed again, 25% of which in the first 5 years, 75% within 10 years and 95% within 25 years. This demonstrates the compelling necessity of profoundly rethinking how existing and new reinforced concrete structures are repaired or designed and built to cope with aggressive environments. Europe has approximately 185000 km of shorelines and, in 2019, counted 130 geothermal electricity plants in operation, with a plan to double this number within next 5-8 years. In addition, in 2019 Europe had 110 offshore wind farms in 12 countries, with more than 5000 grid-connected wind turbines, along with several farms built within coastal areas. These data alone are sufficient to have an idea of the huge number of strategic infrastructures exposed to aggressive environments in Europe, and to clearly see the urgent need of tackling their maintenance demand in order to have more sustainable human development.

Towards the green transition of the construction industry, today, three approaches seem to be viable and worthwhile being explored: (a) to build more durable concrete structures, (b) to produce concrete through cement substitutes, and (c) to reduce the use of fossil-fuel within the cement production process.

The research activity presented in this thesis is framed into the Horizon 2020 project ReSHEALience (GA 760824), and aims to contribute to the first of the afore-mentioned strategies. This study is expected to provide modelling tools for predicting the mechanical and durability performance of both ordinary and advanced cementitious materials in service conditions. An existing physics-based discrete model, the Multiphysics-Lattice Discrete Particle Model (M-LDPM), has been improved to capture the specific features of conventional and innovative cement-based composites. In particular, the two way-coupled framework of M-LDPM has been enriched with new functionalities to capture (i) the moisture permeability increase due to damage, (ii) the autogenous and stimulated healing of cracks, (iii) the healing-induced effect on the mechanical performance in case of both plain and fibre-reinforced composites, (iv) the impact of cracks sealing on permeability and chloride penetration, and (v) the effect of additional cementitious materials on the concrete ageing. On one hand, the revised model has been calibrated and validated against experimental data, in order to demonstrate its improved descriptive nature. Due to lack of laboratory measurements, the calibration of the parameters governing the chemical reactions featuring the material ageing has been addressed by taking advantage of an improved version of the ONIX model.

On the other hand, given the large amount of parameters to identify through extensive and demanding laboratory campaigns, the study also has focused on the exploitation of numerical approaches, based on the fuzzy logic and set theory, to deal with the uncertainty featuring the model calibration in case of limited or none experimental direct measurements. This is expected to contribute to turn the model into a predictive approach. Finally, being the adopted models formulated at either micro- or meso-scale, and well performing for the simulation of laboratory tests, a strategy for taking advantage of its accuracy at the structural level has been identified.

From the comparison between numerical outcomes and experimental evidence it is reasonable to retain that the two way-coupled discrete numerical model and the methodology proposed for the uncertainty modelling and upscaling might represent an additional step towards the capability of predicting the long-term performance of concrete structures.

The improved M-LDPM is able to replicate what is experimentally observed in the reference laboratory campaigns. The model has shown the capability of accurately capturing the material ageing. Not only the evolution of the compression and fracture strengths is well simulated, but also how the failure mode changes with time and specimen geometry.

The modelling approach for crack healing together with the implementation of its effect on moisture permeability has turned out to be effective in capturing the experimental evidence: the healing degrees obtained by means of the model are in agreement with those achieved within the laboratory campaigns for both ordinary and advanced concrete. Furthermore, the discrete approach proposed shows the capability of capturing the local interactions among the most relevant governing factors of the self-healing process in cementitious materials.

It is possible to account for environmental conditions, crack width and local moisture supply. The two-way coupled model when paired with chlorides diffusion model has shown good capabilities in capturing the material behaviour observed in the laboratory. In particular, the model is able to simulate the effect of damage on the diffusion process, and the reduction in terms of chlorides penetration when healing agents are included in the mixture.

Finally, the fuzzy set controller seems to be a valuable tool for the educated guess of the governing parameters when the experimental data are limited or missing. The numerical results gained with the predicted parameters have shown a good agreement with the experimental ones. The relationships assumed as basis of the numerical device can be improved as knowledge advances. The controller could be a powerful tool not only to avoid expensive laboratory campaigns, but also for preliminary analyses in the process of innovative materials design.

An example of the model potential is shown in Fig. 1. It is possible to see the punctual relationship between crack opening and healing degree: the larger crack width, hence the available space for moisture supply, the more pronounced the healing results. The model is formulated in order to ensure this condition holding as long as the crack becomes too large for being healed.

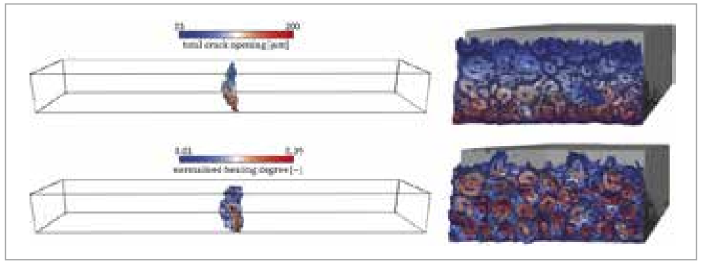

Fig. 1 -Results visualisation - Modelling output in terms of crack opening (top) and normalised healing degree (bottom) after 12-month curing in water immersion

THE PHASE-FIELD MODELING OF FRACTURE EVOLUTION IN DUCTILE MATERIALS WITH APPLICATION TO PAPERBOARD MECHANICS

Alessandro Marengo - Supervisor: Prof. Umberto Perego

Paperboard is one of the many layers composing the layered packaging material employed in the food industry for preservation of liquid products. Its purpose is to provide the mechanical properties to the final package in terms of strength and stiffness.
The yearly production of this kind of packages amounts at several hundred billions units.
This number motivates the intense research activity aimed at characterizing and improving the packaging material to reduce waste. Despite experimental tests may provide useful information, practical applications require a mathematical modeling based on a profound understanding of the material response.
The mathematical description of paperboard response has been extensively explored in the literature in the elastoplastic regime preceding the onset of damage and fracture. The main objective of the current work is to extend the state-of-the-art elastoplastic modeling of paperboard material to include the development of damage and subsequent crack propagation.
In Computational Mechanics, the modeling of fracture evolution introduces the fundamental challenge of dealing with discontinuous displacements.
In the last two decades, the phase-field approach has overcome this problem changing the description of the crack topology. Indeed, the sharp geometry is substituted with a smooth regularization governed by the order parameter called \textit{phase-field}.
In the present work, a computationally efficient and explicit algorithm for the rigorous enforcement of the irreversibility constraint in the phase-field modeling of brittle fracture is presented. The proposed approach relies on the alternate minimization of the total energy functional. The phase-field evolution turns out to be governed by a {complementarity boundary-value problem}, where the complementarity stems from the irreversibility, while the boundary-value problem stems from the presence of the gradient term in the phase-field functional.
A solution strategy based on the Projected Successive Over-Relaxation (PSOR) method for constrained optimization, where an iterative explicit scheme is used for the solution of symmetric linear complementarity problems, is presented.
A variational formulation of ductile fracture, based on a phase-field modeling of crack propagation, is then proposed for isotropic materials both in small and large deformations.
The formulation is based on an effective stress approach, combined with an AT1 phase-field model.
Starting from established variational statements of finite-step elastoplasticity for generalized standard materials, a mixed variational statement is consistently derived, incorporating in a rigorous way a variational finite-step update for both the elastoplastic and the phase-field dissipations.
The complex interaction between ductile and brittle dissipation mechanisms is modeled by assuming a plasticity driven crack propagation model. A non-variational function of the equivalent plastic strain is then introduced to modulate the phase-field dissipation based on the developed plastic strains.
In the context of small strains, a gradient-extended plasticity framework has been proposed to prevent the pathological mesh-dependence due to the combination of the softening response and the continuing plastic deformation induced by the effective stress approach.
Particular care has been devoted to the formulation of a consistent Newton-Raphson scheme for the gradient-extended model in the case of Mises plasticity, with a global return mapping and relative tangent matrix, supplemented by a line-search scheme, for fixed phase field. The resulting algorithm has proved to be very robust and computationally effective.
To approach the phase-field modeling of fracture in paperboard the proposed ductile fracture formulation has been extended to orthotropic materials, being ductility and orthotropy the fundamental features of the paperboard mechanical response.
The resulting orthotropic, small strain phase field model for ductile fracture, based on a state-of-the-art elastoplastic in-plane model, has been applied to the simulation of failure experimental tests on paperboard strips, with excellent results in terms of accuracy and scale independence.
As a first step towards the inclusion in the model of the large strain out-of-plane paperboard behavior, a large strain isotropic elastoplastic model for ductile phase-field fracture has been proposed, based on a variational update of the large strain finite-step elastoplastic phase-field problem.
The gradient extension of the model and its application to orthotropic paperboard are then left for a future development.

METAMATERIALS FOR ENERGY HARVESTING AT SMALL SCALE

Marco Moscatelli - Supervisors :Prof. Claudia Comi, Prof. Jean-Jacques Marigo

The increasing demand of energy-autonomous small electronic sensors and devices has propelled the emergence of energy harvesting technologies as a prominent area of interest for research both in academia and industry. One of the key features of this new generation of sensors is their low-power electricity demand. This characteristic has promoted the development of small-scale integrated solutions as alternatives to the periodic replacement or recharging of commonly used batteries, eliminating, or at least reducing, the costs associated to these procedures (both in terms of economical resources and environmental waste).

In this framework, one of the most effective methods for the energy harvesting is to use ambient vibrations, due to the ease of finding this source of mechanical energy. Nevertheless, ambient vibrations are generally largely distributed in space and characterized by a low energy content. Therefore, for an efficient harvesting of energy, it is required to develop systems that are able to convey and trap the vibrations (and the energy they carry with them) in a small region, where they can then be collected and converted into electrical energy by means of, for instance, piezoelectric devices.

Among the possible solutions, the artificial materials that go under the name of "metamaterials", if properly designed, have proved to possess excellent properties in terms of waves control and can be used to develop vibration-based energy harvesting systems. Here, we will concentrate on a specific attribute that characterizes the dynamic behavior of a class of these composite materials, namely the presence of band gaps in the spectrum, *i.e.* intervals of frequencies corresponding to attenuated waves. Phononic crystals and locally resonant materials with a periodic structure belong to this class and are the main subjects of this work. Using a mass-in-mass crystal, we first individuate the roles of the main parameters of the problem of wave propagation in these two typologies of metamaterials. Then, we employ a two-scale homogenization technique to derive their effective behavior at a sub-wavelength scale. In particular, locally resonant materials are analyzed, being characterized by the presence of band gaps already at a sub-wavelength regime.

With the idea of focusing the mechanical energy in a confined area, we analyze the effect of a defect of periodicity. We show that this can result in the formation of localized modes at frequencies inside a band gap. By using locally resonant materials, we then develop a system (based on the resonant tunneling phenomenon in physics) that allows us to trap mechanical waves in a cavity, *i.e.* in the region of the metamaterial with a defect of periodicity, where the energy will pile up and thus focus. We make here use of the derived effective material properties.

In the final part of the manuscript, we study and experimentally validate the attenuation and localization phenomena on a one-dimensional metastructure. For this, we employ a taut cable with a family of hanging masses periodically repeated along its length. First, we theoretically study its dynamic behavior and then we compare the results with an experimental test, validating the attenuation and localization effects.

The objective of this thesis is twofold: on one hand we aim to treat the elastodynamic problem associated to defective periodic media presenting band gaps (*i.e.* metamaterials), and on the other hand we also want to give some proofs of efficiency of these systems for the localization of mechanical energy. Our results provide new insights on the dynamic behavior of defective periodic media to be used in energy harvesting systems, which makes this work relevant to both theoretical and practical fields.

THE DIRECT PARAMETRISATION METHOD FOR INVARIANT MANIFOLDS: DEVELOPMENT AND APPLICATION TO LARGE DIMENSIONAL FINITE ELEMENT MODELS OF MEMS STRUCTURES

Andrea Opreni - Supervisor: Prof. Attilio Frangi

Co-Supervisor: Prof. Cyril Touzé

Micro-electro-mechanical systems (MEMS) represent a fundamental piece of our economy and life. Indeed, their small size combined with high sensitivity to external stimuli allows adopting them as sensors and actuators in most technological components as cell-phones, earphones, and smart glasses. Nevertheless, the high demand of MEMS devices makes this industrial field competitive and it forces companies to achieve constant improvements of their products to thrive in the market. As a result, precise and accurate mathematical methods to predict the response of MEMS devices are essential tools since traditional "trial and error" approaches are not sustainable considering the high costs of the fabrication process.

Among the different classes of mathematical methods adopted in industry, full order solution methods are the most common techniques since they are reliable and accurate when it comes to elaborated geometries that cannot be modelled by analytical methods. Their efficiency is however lost when modelling devices that need to operate at resonance since steady state periodic solutions are computational demanding for large scale systems of differential equations. The result is that resonating devices i.e. devices that operate at resonance as MEMS gyroscopes and micromirrors, are challenging to design and optimise using full order methods. The consequence of this limitation is the necessity to adopt model order reduction strategies i.e. techniques aimed at reducing the computational complexity of numerical models. Among the different methods available in literature the parametrisation method for invariant manifolds (PIM) represents one of the most appealing techniques for dimensionality reduction of nonlinear systems since it provides a mean to derive reduced models by parametrising the system motion along a low dimensional invariant set of the phase space. This approach has several benefits compared to other model order reduction strategies since it exactly addresses non-resonant coupling, the latter the cause of failure of energy-based approaches as the proper orthogonal decomposition followed by hyper-reduction.

In the present work, a direct formulation of the PIM is proposed. The technique is based on the introduction of nonlinear coordinate change between nodal variables of a finite element model and normal coordinates i.e., the coordinates defined over the parametrised set. Explicit relations and computational aspects of the method are detailed and the resulting algorithm shows performance that make it one of the most efficient dimensionality reduction methods for nonlinear vibrating structures.

The manuscript is divided into three parts. In the first part, an overview of models and numerical methods applied to nonlinear microstructures is provided. First, the partial differential equations that govern the dynamic of nonlinear microstructures are provided. Then, the finite element method is introduced as technique to derive a system of differential equations for the problem. The first parts is then closed with a derivation of numerical methods for the computation of periodic orbits in nonlinear systems. Periodic orbits represent an important class of solutions in MEMS that operate at resonance and their computation is of uttermost importance. The second part of the work details theory and algorithmic aspects of the direct parametrisation method for invariant manifolds (DPIM). The method is first introduced for autonomous systems. Periodic solutions of the conservative autonomous mechanical problem are computed with the DPIM for structures of industrial relevance. Furthermore, we detail phenomena that cannot be modelled with other model order reduction methods as for instance folding points in invariant sets. This is shown on a cantilever structure discretised with finite elements. The method is then extended to non-autonomous problems for the computation of frequency response curves of the device. In practical applications, damping and external excitation are always present and as a result proper treatment of external excitations during model reduction is essential to identify phenomena as parametric excitation, isolated branches of frequency response curves, and the effect of externally excited non-resonant modes on the dynamics of the system. All theoretical results are shown on structure of both academic and industrial interest.

The third and last part of the work details the application of the method to real structures: MEMS micromirrors subjected to piezoelectric actuation. Piezoelectric actuation represents the most promising technique for MEMS devices that need to undergo large amplitude motion and it is likely to be the driving technology for the next generation of optical devices and smart glasses and lidar systems. In this part of the work a comprehensive model order reduction scheme for nonlinear piezoelectric structures based on the DPIM is derived and numerical results are compared with experimental data obtained on real MEMS microstructures. Overall, the presented work represents one of the major results in model order reduction methods for nonlinear vibratory systems and the DPIM can be considered as the most efficient method for design and optimization of resonating MEMS devices.

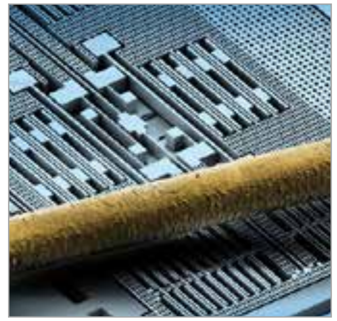

Fig. 1 - Scanning electron microscope image of a MEMS device. A human hair is reported for scale.

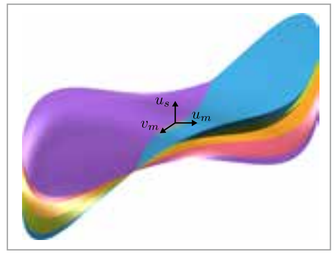

Fig. 2 - Whisker attached to an invariant torus perturbed from a hyperbolic fixed point. It represents one of the structures modelled using the DPIM.

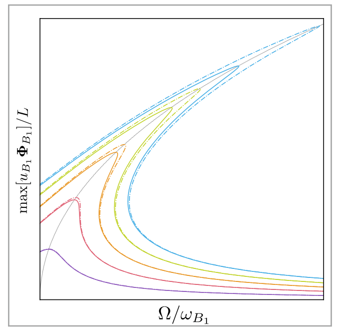

Fig.3 - Frequency response curves computed for a forced-damped cantilever beam subjected to transverse loading.

BLENDING PHYSICS AND DATA IN STRUCTURAL HEALTH MONITORING

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Co-Supervisor: Prof. Stefano Mariani

Safety of civil structures is a key challenge in our society. In recent years, catastrophic failures of bridges and buildings has impacted on public opinion becoming a major concern for policy makers and regulators. In situ inspections alone cannot address the need for safe structures and infrastructures because they assess structural performance at the moment of the inspection. Monitoring systems collecting data and assessing the damage state of a structure in real time are needed. This is the field of Structural Health Monitoring (SHM), in which data are continuously recorded. It is impractical to have an expert continuously looking at the data inflow; therefore, the process of extracting damage sensitive information from data and of employing this information for structural performance assessment must be automated as much as possible.

For this purpose, the pattern recognition paradigm is exploited. This methodology can be applied both when data based approaches and model based approaches are used. While model based approaches, working by simulating the response of the structure and by comparing it with incoming measurements, seem preferable to assess the remaining useful life of the monitored building, data based approaches cope better with the great amount of noisy data typically acquired by monitoring systems made up by pervasive sensor networks. The main drawback of data based approaches is that data related to the possible damage conditions of the structure before the onset and propagation of the damage itself are not available: this prevents from employing supervised machine learning algorithms from the calibration of the statistical model that, according to the pattern recognition approach, accounts for the mapping between reduced and meaningful representation of the data, the so called features, and the possible damage conditions affecting the structure. Thus, unsupervised learning algorithms must be employed. However, unsupervised learning usually leads to statistical models poorly describing the possible current damage scenarios, being usually limited to damage detection and, at most, localisation.

Simulation based classification is demonstrated able to mitigate such a drawback by employing physics based models simulating the effect of damage on the structural response, and by using simulated data to enrich the dataset employed by data based approaches. In this way, the adoption of supervised learning paradigms is enabled. This approach is successful if the probability distribution underlying simulated data is the same of experimental data even when damage occurs and propagates. According to the experience gained by the research community in vibration based structural identification techniques, damage is modelled as a localised stiffness reduction. Deep learning is adopted to automatise data processing and fusion by exploiting the capacity of fully convolutional networks of extracting features optimised for the demanded classification task from vibrational recordings, usually shaped as multivariate time series. Dataset construction is accelerated by exploiting reduced order modelling in elasto-dynamics and by the efficient sampling, through latin hypercube, of the parameters ruling the mechanical properties of the structure and the operational conditions. Reduced Order Modelling (ROM) is performed via reduced basis, a numerical technique addressing problems governed by parametrised partial differential equations.

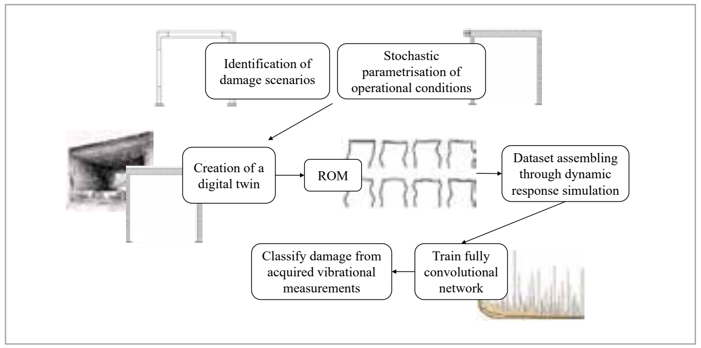

Fig. 1 - Simulation based classification approach to structural health monitoring.

As a result of a case study involving a shear building, damage is correctly classified among nine possible alternatives up to 95% of cases, while the accuracy for the portal frame structure attains at least the 80% even for high signal to noise ratios. For the latter case study, the use of reduced order modelling allows to shorten the simulation time by a factor 30, enabling a considerable speed up in the dataset construction.

To reduce uncertainty related to loading conditions, a neural network based autoencoder employing inception modules and residual learning in the encoding and decoding parts is designed to obtain an extremely reduced set of generative latent variables describing the monitoring data, shaped as multivariate time series. Autoencoders are unsupervised learning algorithms, but, since latent factors are redundant and strongly correlated, and since it is impossible to give a physical meaning to them just by judging their values, a second neural network, trained in a supervised manner, is used to perform load identification starting from the latent representation.

The physics based model employed in the simulation based classification approach enables to compare and update the knowledge exploited to construct the numerical model of the structure with the incoming data. The numerical model is used to simulate the dynamic response of the structure in a wide spectrum of possible load conditions and damage scenarios. Fully convolutional networks match simulated data with experimental data, finally enabling damage detection and localisation. However, it is desirable to have a digital twin continuously updated by comparing its predictions with incoming data, and not limited to identify possible damage conditions.

For this reason, attention is paid to filtering techniques. Filtering techniques enable a rich description of the monitored structural systems, and allow to treat, in a unified Bayesian context, both the uncertainties related to the assumptions underlying the construction of the digital twin, and the uncertainties related to the model calibrating parameters. With this goal, a model class plausibility formula is tested for the unscented version of the Kalman filter. The unscented Kalman filter is preferred with respect to the extended Kalman filter for its more straightforward implementation, and because it introduces smaller approximation errors with respect to the linearisation implied by the extended Kalman filter when non linear systems are treated. Two analyses referring to the same shear building model, one in undamaged conditions and the other featuring the occurrence of an inter storey stiffness reduction, are carried out to evaluate the performance of the model class evidence formulation: in both cases, the best parametrisation of the model is correctly detected, and the corresponding model plausibility, expressing in probabilistic terms the relative degree of belief in a certain model class with respect to the others, is pushed to one.

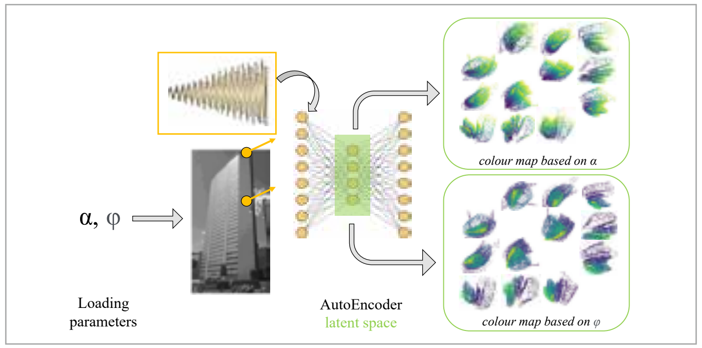

Fig. 2 - Autoencoder-based load identification procedure.

INTENTIONAL AND INHERENT NONLINEARITIES IN ADVANCED PIEZOELECTRIC VIBRATION ENERGY HARVESTING

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Co-Supervisors: Prof. Alberto Corigliano, Prof. Alper Erturk

Our times are characterized by the ever-increasing need to have interconnected networks of smart objects that exchange data between them. This concept takes the name Internet of Things (IoT). The purposes of having interconnected networks are mainly related to observe the environment around us which, technically, takes the name of monitoring and it is done through sensors. Often, such observation is then exploited to perform further operations through actuators. The application of the concept is very huge and covers different fields, such as monitoring of medical, structural and infrastructural parameters or machinery control. The last few years have seen the inclusion of monitoring systems even in the field of recreation activities and sports, given the spread of smart technology goods in consumer markets (smartphones, smartwatches and so on). As a consequence, what has been discussed, the insertion of very high quantities of sensors in the environment is required. These should not be invasive in the physical space and, at the same time, they should not consume large amount of energy both for maintenance costs and environmental reasons. It is desiderabile for them to be completely autonomous in terms of energy consumption. On the one hand, the issue of invasiveness can be solved by the so-called Micro Electro-Mechanical Systems (MEMS), which are devices that exploit the silicon technology to integrate electrical and mechanical components at the small scale. On the other hand, the issue of the energetic consumption, can be solved by environmental energy harvesting techniques. Among many possibilities, one promising technique is the exploitation of the mechanical energy of the environmental vibration and its conversion into electrical energy through piezoelectric materials. The combination of the two concepts brings with it a large number of fascinating challenges, some of them purely scientific that involve different Physics area: mechanics, advanced material sciences, and electromagnetism.

Other challenges are related to the purely technological and industrial development aspects. In this context this doctoral thesis fits. More in detail, this work presents recent detailed investigations on the magnetic frequency up-conversion (FuC) for piezoelectric energy harvesters and its implications. The main original contributions of thesis are the listed in the following.

Theoretical, computational and experimental investigations of the magnetic force for frequency up-converting piezoelectric vibration energy harvesters.

Highlighting in a theoretical, computational and experimental framework the dependency of the dynamical response of magnetically actuated oscillators on the interaction velocity and its scientific implications. It is pointed out that the magnetic FuC is not a frequency-driven phenomenon. Highlighting the practical limits of this technique in the context of low-velocity energy harvesting. Proposal of a magnetic shielding technique to overcome the operational limitation of the classical magnetic FuC technique.

Design, prototyping and testing of a piezoelectric vibration energy harvester based on the combination of magnetic plucking and indirect impacts.

Study of electromagnetic levitation-based phenomena for motion of a mass or a collateral mechanism (i.e. when the plucking does not occur) for energy scavenging.

Consideration of observed inherent material nonlinearities in modelling magnetic plucking phenomenon for piezoelectric vibration energy harvesting.

Design and analysis of a MEMS piezoelectric energy harvester compatible with the existing microfabrication process for Piezoelectric Micromachined-Ultrasound-Transducers (PMUT). This part is developed in collaboration with the industry STMicroelectronics.

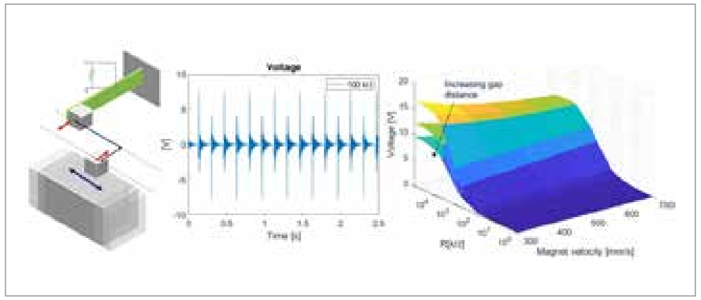

Fig. 1 - From left to right: schematic of a typical magnetic frequency up-conversion mechanism, example of instantaneous voltage experimental response, RMS voltage in the case of parametric analyses.

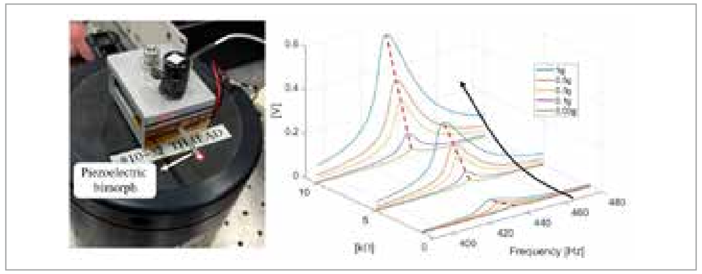

Fig. 2 - Typical piezoelectric bimorph mounted on a shaker (left) and related experimental frequency response functions of electrical voltage (right). The red dashed lines represent the backbone curves of the system that is inherently nonlinear due to softening of the piezoelectric material.