Chair:
Prof. Roberto Paolucci

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Objectives of the Doctoral Program

Structural, Seismic and Geotechnical Engineering - SSGE consists of the disciplines and techniques that allow to understand, model and control the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials and materials for micro-systems), (b) structural systems (from constructions to bio-mechanical systems and micro-systems), (c) soils, and (d) environment-construction interaction. Being deeply-rooted in Civil Engineering, which is – by its own nature – highly inter-disciplinary, SSGE focuses also on the environmental actions, either external (like earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction (like those caused by retained-earth thrust, landslides and water-table fluctuations). Because of their generality in materials and structural modeling, the methods developed within the domain of SSGE are very advantageous also in other technical-scientific domains, whenever understanding and controlling the mechanical aspects are necessary to guarantee both design reliability and structural safety, serviceability and durability. Many are the examples of the issues typical of SSGE: from tall buildings and bridges to industrial bio-mechanical and micro-electromechanical systems, from off-shore structures and dams to the rehabilitation of monumental buildings, from seismic design and structural dynamics to slope stability, tunnel behavior and foundations, not to quote many issues that are in common with several branches of Industrial Engineering. Within this context, the primary objective of this Graduate School is to favor the advancement of the knowledge, with reference to: (a) innovation in materials and structures; (b) building safety under highly-variable actions; (c) soil and surface/buried structure stability. This objective is pursued by giving the PhD Candidates an advanced, research-oriented formation, based on the pivotal role of Structural Engineering and on the multi-disciplinary nature of Seismic and Geotechnical Engineering.

Contents of the Doctoral Program

Attainment of a PhD in Structural, Seismic and Geotechnical Engineering requires study and research activity of at least three years full-time equivalent study, research and development of the PhD thesis, with a minimum of 35 credits from PhD level courses.

The Candidates are offered several advanced courses on a variety of topics concerning materials and structural mechanics, computational and experimental methods, and structural reliability, the focus being always on

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

The main objective of the activity of the PhD candidate is development of an original research contribution, which must be coherent with the research topics developed in the department in which the PhD Programme is carried out, and its publication in the form of a PhD thesis. In such thesis, the objectives of the research work should be clearly stated in the context of the state of the art of the research field and the methods and original results presented and discussed. The PhD research will be developed under the guidance of a supervisor.

To earn credits and to start or to refine their dissertation, the Candidates are strongly suggested to spend a period abroad, in one of the universities or research centers that have systematic scientific relations with the Politecnico di Milano. At the same time, the PhD School favors the visit of foreign scholars, to give short courses in Milan. In this way, the Candidates are offered a number of opportunities to interact with the international community.

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MEMS SENSORS FOR MEASURING THE EARTH MAGNETIC FIELD: MECHANICAL ASPECTS

Mehrdad Bagherinia - Advisors: **Prof. Alberto Corigliano, Prof. Stefano Mariani**

The electronic compasses found application in low power devices, such as cell phones and portable Global Positioning Systems (GPS). Navigation magnetometers use the Earth's magnetic direction or magnitude to determine direction. The Earth's magnetic field varies place to place on Earth but ranges between –.

In electronic applications, there are several requirements for the magnetic field sensors. Besides having enough sensitivity and resolution to measure the direction of the Earth's magnetic field, it is essential to have small size and low power consumption while being compatible with CMOS fabrication. Micromachining process enables such a sensor to be fabricated in a micron size with CMOS compatible processes. Low-cost batch production is also another advantage of the micromachining process. Microelectromechanical systems (MEMS) are micron-size devices that combine electrical and mechanical components to sense or manipulate (actuate) the physical world. MEMS are fabricated using micromachining processes, developed initially for integrated circuit industry, to add mechanical elements such as beams, gears, diaphragms and springs to devices. This allows a mechanical system to be fabricated in a very small

area, typical of an IC device. MEMS are typically fabricated on silicon wafers and due to their size, tens of thousands of these devices can be fabricated on a single wafer to significantly decrease the cost of mass production. Examples of MEMS devices include e.g. inkjet-printer cartridges, microengines, mircropumps, micromirrors, inertial sensors (i.e. accelerometers, gyroscopes and magnetometers).

The goal of this project was to study, design and optimize novel micromachined MEMS sensors for Earth magnetic field sensing which has found various applications in electronic devices. Based on some specifications determined by the industrial sponsor of this project, STMicroelectronics, it was also intended to not use special processing steps or non-standard materials for the fabrication

of the devices, hence the sensors could be manufactured in standard micromachining processes. Moreover, it was favored to design the sensors structure in such a way that they filter the acceleration noise intrinsically by design, without further electrical filters.

This work starts with multi physics modeling of MEMS magnetometers. To provide a frame for new designs and modeling, a multi-physics model of a beam, considered as a characteristic component of Lorentz force magnetometers, subjected to Lorentz force and electro-thermo-mechanical loading has been described. As shown in Fig. 1, due to an voltage difference between anchorages, an excitation current can flow along the beam. If the frequency of equals to the vibrating beam resonant frequency, when
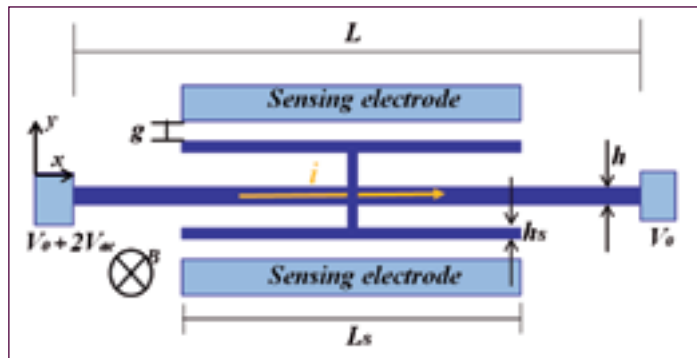
1. The characteristic component of a capacitive magnetometer.
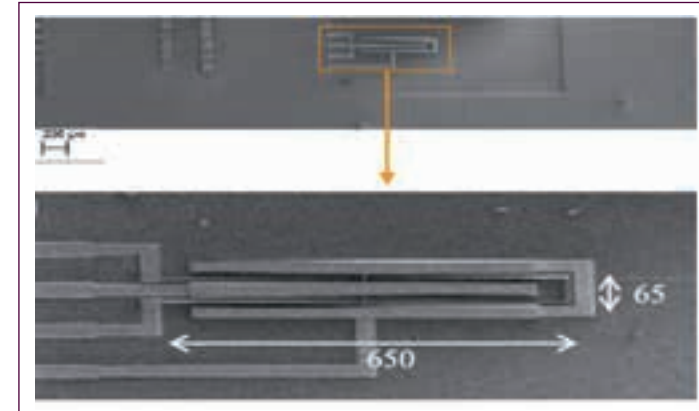
2. SEM images of the experimentally tested HDETF structure (dimensions in µm).

the beam is exposed to an external magnetic field in the out-of- plane direction, then a mechanically distributed Lorentz force is generated in-plane, perpendicular to the beam axis, and accordingly the beam will deflect.

Based on the STMicroelectronics technology and the provided framework, two ideas for MEMS uniaxial magnetometers out of the acoustic bandwidth are proposed, designed and fabricated: a Half Double Ended Tuning Fork (HDETF) structure and a frame-like structure. The fabricated HDETF sensor (see Fig. 2) has been tested. The test set up that was exploited to process signals of this sensor has been described and the experimental results have been also compared to the best sensors found in literature (see Table I). By comparison, it can be concluded, in spite of occupying a very small die area, this sensor provides a good balance between important performance indexes (Brownian noise-limited resolution, bandwidth and sensitivity), so that it can be considered as an efficient

magnetometer. Moreover, it can mechanically filter parasitic accelerations.

Since, the design variables of the Half-DETF structure were chosen by a trial-and-error procedure, optimality of this device is obtained by means of a structural optimization approach. A wide scenario of design configurations, obtained with the proposed optimization approach, is discussed. Multi-axis sensing and sensor integration is the trend of MEMS inertial sensors as they allow chip size and fabrication cost to

be reduced, while maintaining the same performance and reliability. At the end, a new idea for single-structure 3-axis magnetometers has been given. Different aspects of this work can be used for design and modeling of other MEMS devices and systems. Results of the presented modeling framework can be adapted and adjusted to investigate the behavior of many of the micromechanical devices. Also the proposed structural optimization approach can be widely exploited to optimize various devices in MEMS field.

Table I
Comparison of performance indexes of current and available Lorentz force magnetometers.

Publication	Axis	Resolution (nTmA/$\sqrt{Hz}$)	Dimensions (µm)	BW (HZ)	Mass (KG)
This work	Z	115	650 x 65	60	5 x 10^{-10}
Li et al.	X/Y	500	1080 x 800	69	9.7 x 10^{-9}
Li et al.	X/Y	88	200 x 1000	2.3	8 x 10^{-10}
	Z	55	200 x 1000	7.4	
Thompson et al.	Z	235	2000 x 1000	1	6.8 x 10^{-9}
Kyynarainen et al.*	Z	7	2000 x 400	2	1.2 x 10^{-9}

* This device features an extra metal layer
**Estimated data

TENSILE STRUCTURES: BIAXIAL TESTING AND CONSTITUTIVE MODELLING OF COATED FABRICS AT FINITE STRAINS

Giada Colasante - Supervisor: **Prof. Giorgio Novati**

This thesis deals with the mechanical characterisation and constitutive modelling of coated fabrics that are employed in tensile membrane structures. These are made of thin surfaces that can carry only tension and no compression or bending; therefore they represent highly efficient structural forms, which require specific knowledge to be designed. The rapid growth of this structural typology has led to heterogeneity of the current design procedures and to fragmentation of the technical knowledge that membrane producers have at their disposal. These two aspects are partially linked to the absence of European standards on membrane structures.
A series of contributions are provided in this work, which are in line with the objectives of the Research Cluster on "Innovative Textiles" (ClusTEX) that has been created in 2008 at Politecnico di Milano, with the aim of systematising and enhancing the expertise currently possessed by several research units on the subject of advanced composites. First, an extensive literature review is carried out, to assess the current state of the art about the analysis and design of tensile structures. The multiplicity of methods employed in the form-finding and cutting pattern generation stages is described within a unified framework.

The scarcity of references about cutting pattern highlights the need of further research and may be partially attributed to the absence of reliable constitutive laws for the description of the first-loading behaviour that coated fabrics undergo during installation.
Then, the thesis focus is put on membrane materials for tensile structures. These are mainly composite materials made of a polymeric matrix, reinforced by means of woven yarns. The production process and the main technical characteristics of these composites are described. The mechanical behaviour of coated woven fabrics, which turns out to be extremely dependent on their internal meso-structure, is deeply explored. The experimental results obtained from uniaxial and biaxial tests, which have been performed directly by the author, are also commented.
The complex anisotropic nonlinear behaviour of coated woven fabrics is not adequately modelled in the current design practice, which often employs the orthotropic linear elastic constitutive law. On the other hand, the constitutive models used for research purposes are often too complex and computationally expensive. Within this framework, hyperelastic modelling at finite strains seems to be promising

to efficiently reproduce the response of such materials.
A new model is proposed in this thesis, which has been created by adding a term to the free-energy of the existing Holzapfel-Gasser-Ogden model for biological tissues. This new energy component has been thought to capture the strong interaction between the warp and fill yarns which is due to the weaving (crimp interchange). The proposed model is calibrated for different materials, by employing the biaxial test data previously presented. A validation of the new model is performed through some simple benchmark problems, of which the analytical solution is evaluated with a code developed by the author with Mathematica software. The comparison of the results with experimental data shows that the model can reproduce well the stress-strain behaviour of coated woven fabrics for uniaxial and bias extension tests, as well as for biaxial tests.
Finally, the new constitutive law is implemented into a user subroutine for ABAQUS, and the same validation examples are solved numerically, with results that are close to the analytical solution. This implementation into a general purpose finite element software opens the doors to the application of this model to structural design.

However, some numerical issues have still to be solved: extremely large stresses at very large strains, difficulty of Newton's method in predicting a reasonable displacement correction when the stiffness is law, discontinuous derivatives of the strain energy due to deactivation of the some terms when fibres are shortened. These are all aspects that would deserve further studies, aimed at improving the efficiency of the solution algorithm.
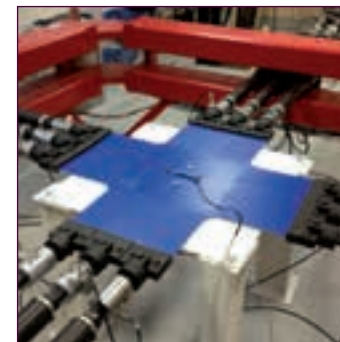
1. Biaxial tensile test on a cruciform specimen.

MULTILAYER PRECAST FAÇADE PANEL: STRUCTURAL OPTIMIZATION FOR ENERGY RETROFITTING

Giorgia Colombo - Supervisor: **Prof. Marco di Prisco**
Co-supervisor: **Dr. Matteo Colombo**

In Europe residential and commercial buildings are responsible of about 40% of the total energy consumption and the 70% of this energy is used for heating. To reduce this consumption, Standards introduce limits to guarantee the energy saving in new buildings, but also the energy retrofitting of existing buildings has to be considered, because of their large impact on the phenomenon.

In this perspective a multi-layer prefabricated façade sandwich panel characterized by an internal EPS layer and by two external layers of Textile Reinforced Concrete (TRC) is proposed. Just the insulating material is used to transfer the shear between the external TRC layers. The maximum size of the panel is 1.50x3.30 m²; the panel height is properly chosen in order to fix it to the frame concrete beams by means of four punctual connectors placed near to the four corners.

The main advantages of this solution if compared with the thermal coating (EIFS system) are: the lower impact on occupant life (no scaffoldings required), the possibility to obtain the desired finishing in terms of surface roughness, colour, pattern (including the reproduction of the original façade), the higher quality of finishing and the higher durability. The latter aspect is particularly important, especially considering a residual expected building life of at least 30 years. Aesthetic and durability aspects are directly related to the use of a high strength fine-grained concrete in TRC.

An innovative in-pressure casting technique is adopted to avoid the use of glue and to prevent the debonding between the layers thanks to the good bond obtained during the production. The main goal of the work is to provide the mechanical characterization of this panel. The research was developed at material, cross-section and full-structure level.

Material level includes the investigation performed on TRC specimens in order to assess their behaviour in tension, considering both standard and extreme conditions (residual strength after exposure to freezing and thawing cycles). At lab-scale level, failure modes of the sandwich solution have been investigated. In particular, small (550x150 mm²) and big (1200x300 mm²) sandwich beams, characterized by the stratigraphy described above, were tested according to a four point load scheme (Figure 1). Both geometries were tested in standard conditions, and small beams were also tested after the exposure to freezing and thawing cycles. Furthermore, the behaviour of the sandwich solution when loaded with a concentrated load was investigated.

Concerning full-scale level, tests were developed considering a real panel simply supported on four points and loaded initially with a distributed load, in order to assess the Serviceability Limit State behaviour, and then with concrete blocks up to failure (Figure 2), in order to determine the maximum load brought. In parallel, a standard modelling of sandwich structures has been performed and the models adopted have been validated with respect to the collected experimental results. Two models were proposed: a literature analytical model, implemented in order to take into account material non linearity, and a finite element model, built in Abaqus FEA software by using default material models.

Basing on the research results, some significant conclusions can be drawn:

· a multi-layer precast façade panel, characterized by external TRC layers, has been proposed as a durable alternative to thermal coating;
· the sandwich behaves as a partially composite panel and is characterized by a ductile behaviour: the ductility is guaranteed by the multi-cracking of TRC layers followed by the shear band development in the EPS layer; the kinematic response of the sandwich solution is governed by the shear behaviour of EPS;
· the damage introduced by freezing-thawing effect is aligned with that of a high performance concrete. Two opposite main phenomena can be identified: the damage of the matrix due to cycles and the activation of self-healing and late hydration; in sandwich samples the exposure to cycles affects mainly the ductility of the beams;
· considering modelling, a good agreement between experimental results and analytical-numerical global responses were found in all the simulations; hence, it is possible to state that the assumption of perfect bond is reliable considering in-pressure cast sandwich specimens.

The investigation suggests to treat TRC as an homogeneous material constituted by fabrics embedded in the matrix, and not – as reinforced concrete – simply as the union of two materials with distinct constitutive laws. Considering the use of TRC in a composite, the main question is how to characterize it for the structural design of the element:

· in uniaxial compression, the contribution of the fabric does not play a key role, hence its presence can be neglected and the mortar can be characterized by following standard procedures;
· the tensile behaviour can be identified starting from tensile tests. At SLS, test results allow to define the constitutive law; at ULS, the Effectiveness Factor (EF) is proposed to be used in order to account for the fabric-matrix interaction;
· concerning bending, the use of a tensile constitutive law determined from tensile tests allows to properly predict bending behaviour of TRC specimens reinforced in the same way up to a certain thickness.

1. Four point load test on big sandwich beam.
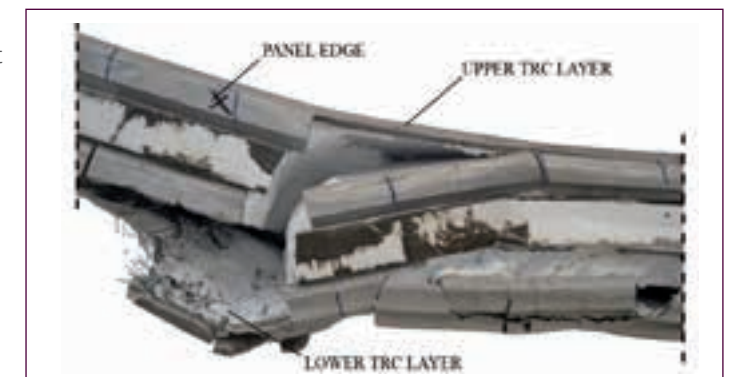


2. Failure of the real scale panel.

SEISMIC PERFORMANCE OF PRECAST STRUCTURES WITH DISSIPATIVE CLADDING PANEL CONNECTIONS

Bruno Alberto Dal Lago - Supervisor: **Prof. Fabio Biondini**

The inadequate seismic behaviour of the cladding panel connections of precast structures and the consequent failures occurred under recent earthquakes in Southern Europe showed that a revision of the technology and design philosophies adopted for this type of systems is necessary. To solve this problem, a general framework for seismic design of precast structures based on innovative fastening systems of the cladding panels is proposed. In this framework, the stability of the cladding panels under seismic action is ensured by means of a dissipative system of connections in between the panels that allows to control the level of forces and to limit the displacements. The proposed connection systems consist of friction-based or plasticity-based devices inserted in between panels, that are connected to the structure through a statically determined arrangement. In this way, the panel-to-panel connections lead the cladding panels to become integral part of the whole façade, making it much stiffer up to the limit force associated with the friction threshold or yielding of the devices. Plasticity-based dissipative connectors to be inserted between columns and panels are also proposed and investigated. The technological aspects and design choices of

materials and shapes leading to a stable hysteretic behaviour of the dissipative devices are discussed and subjected to experimental verification at Politecnico di Milano by means of monotonic and cyclic tests carried out on single devices (Figures 1.a and 1.b), as well as on full scale two-panel structural sub-assemblies with dissipative connections (Figure 1.c). The silicone sealant, that is generally interposed in between the panels, is also mechanically characterised through experimental testing. Design guidelines for single devices are derived based on the interpretation of the experimental results. Capacity design procedures for structural sub-assemblies and systems are also developed based on the mechanical characteristics of the dissipative connectors. The efficiency of the proposed approach is demonstrated by means of non-linear dynamic analyses of typical precast frame-panel structural systems, as well as through a further experimental campaign carried out at ELSA Laboratory of the Joint Research Centre of the European Commission on a full-scale prototype of a precast building with cladding panels (Figure 1.d). This experimental program includes pseudo-dynamic and cyclic tests on structural assemblies provided

with vertical and horizontal panels and different types of connection systems, including the friction-based panel-to-panel dissipative connections tested at Politecnico di Milano. Numerical simulation of the pseudo-dynamic and cyclic tests is performed to calibrate the modelling criteria provided in the design guidelines and to validate simplified procedures for the estimation of the maximum drift attained during a seismic event. The role of the diaphragm action on the efficiency of the proposed connection systems is finally investigated by means of dynamic nonlinear analyses carried out on a set of precast buildings with different plan geometry and distribution of the earthquake-resisting system. The results confirm the remarkable improvement of the seismic performance of precast structures based on the beneficial effects of cladding dissipative connections, which can provide suitable energy dissipation capacity and limit forces and displacements when the effectiveness of the horizontal diaphragms is ensured.

(a)   (b)   (c)   (d)
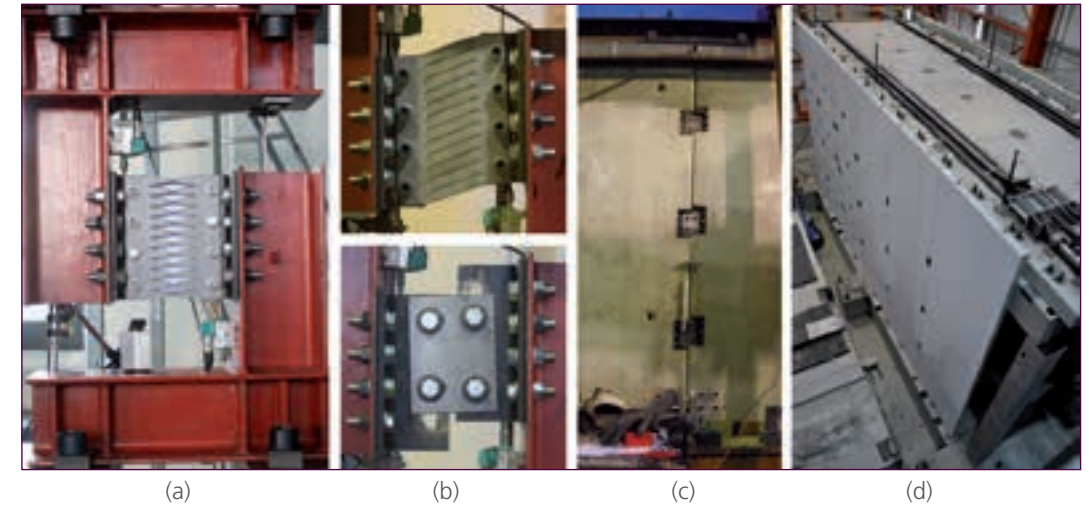
1. Setup of experimental tests on dissipative devices carried out at Politecnico di Milano: (ab) local tests on dissipative connectors; (c) tests on a two-panel structural sub-assembly. (d) Fullscale prototype tested at ELSA Laboratory (JRC).

COMBINED MODEL ORDER REDUCTION AND DOMAIN DECOMPOSITION STRATEGIES FOR THE SOLUTION OF NON-LINEAR AND MULTI-PHYSICS STRUCTURAL PROBLEMS

Martino Dossi - Supervisors: **Prof. Alberto Corigliano** and **Prof. Stefano Mariani**

During the last years, a great progress has been made in computational science and engineering. Higher-fidelity mathematical models, better approximation methods, and faster solution algorithms have been developed for many applications. However, for many time-critical problems, numerical simulations are so computationally intensive that they are either too slow to satisfy the problem's time constraints (i.e. real-time or quasi real-time simulations, e.g. in biomedical applications, forecast weather simulations, structural health monitoring, adapting design and computer graphics research) or they can not be performed as fast as needed. As a consequence, in different engineering fields there is a growing interest in developing techniques which allow to obtain an approximate solution of nonlinear complex problems; multi-scale computational strategies have been developed to tackle this important issue, such as enrichment techniques, homogenization strategies, and the **Domain Decomposition** (**DD**) method. Together with these techniques to obtain an approximate solution to generate low-dimensional and low-complexity computational models, the development of the **Model Order Reduction**
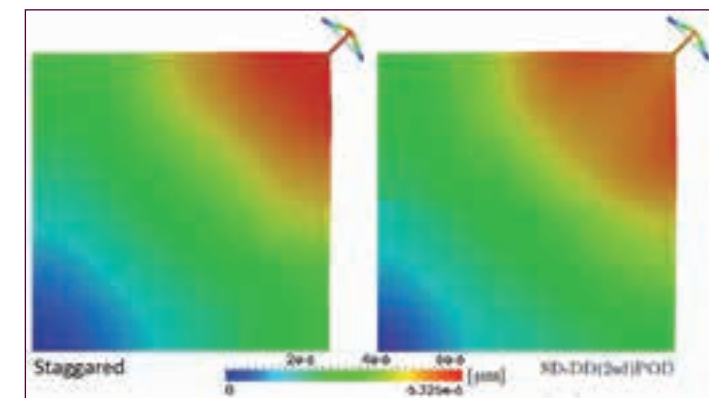
(**MOR**) methods appear to be promising in alleviating computational demands with, potentially minimal loss of accuracy.
In this work, the coupled use of Domain Decomposition (DD) methodologies together with model order reduction techniques based on the use of Proper Orthogonal Decomposition (POD), is proposed. Starting from the DD technique proposed by Gravouil and Combescure (2001), the DD algorithm used in this work is characterized by the enforcement of displacement continuity between initially decoupled sub-domains. Three model order reduction techniques coupled with DD are presented
First, a new strategy for the efficient solution of highly nonlinear elastic-plastic structural dynamic problems is proposed. Applying the standard version of the POD in dynamics, the resulting reduced order model is generally poor at capturing the dynamical response of the system in entire input space, especially in the case of the presence of the evolution and irreversible phenomena, e.g. plasticity. Against this drawback, the idea is the adaptation of the POD basis with two different updating strategies: first, during the training part of simulation

(i.e. when the reduced bases in each sub-domain are constructed), the reduced space is continuously updated, as soon as a new snapshot (i.e. the response of the system in a time instant) is collected; second, an on-line update of the reduced space, which allows increasing the versatility of the algorithm. During the reduced fast analysis a behaviour check is implemented, to control if the linear elastic hypothesis in each sub-domain remains valid. The POD is applied to domains that remain elastic; in those parts of the structure in which the non-linear phenomena occur, the POD reduced analysis stops, and, through a zoom-in strategy, the non-linear modelling is performed. The rich non-linear and reduced linear regions are analysed simultaneously and are glued together through interface relations. The applications show that the computation time necessary for solving elastic-plastic problems can be reduced of approximately 50%, while keeping accuracy comparable to that of the full model solved with a classical monolithic approach.
Second, an innovative numerical procedure, based once again on the combined use of a DD technique and of a POD methodology, is proposed, to simulate multi-physics electro-static structural dynamic

problems. In the design and reliability assessment of Micro Electro Mechanical Systems (MEMS), based on realistic simulations of complicate multi-physics processes, e.g. the electro-mechanical, the thermo-mechanical and the magneto-mechanical ones an accurate solution is required. This kind of complex and usually non-linear coupled problems lead to situations with large numbers of degrees of freedom, which are prohibitive to solve with standard finite element model. Apart from geometric and material nonlinearities, it is most often the coupling between the mechanical and the electrostatic domain, which causes, because of the deformation of the simulation boundary, non-linear terms in an otherwise linear problem. For this reason, one of the goals of this project is to show how the combination of a DD technique with the POD, can give rise to an algorithm which efficiently solves the non-linear electro-mechanical coupled problem (see e.g. Fig. 2). The electro-mechanical dynamic analyses show computational gains up to 98%.
Finally, the coupled use of DD and POD is used for the simulation of fracture problems under dynamic conditions. Assuming that cracks can propagate only inside one sub-domain, the fracture

process is modelled according to the method proposed by Confalonieri (2013); the POD is applied to sub-domains that remain elastic. Examples of

1. Plane resonator subjected to time-invariant actuation: maps of in-plane displacement field. Comparison among the solutions obtained with a staggered approach, and with the proposed SD-DDPOD methodology.

fracture propagation (see e.g. Fig 2) show as the coupled use of DD and POD allows to obtain a reduction of the computational burden up to almost 30%.
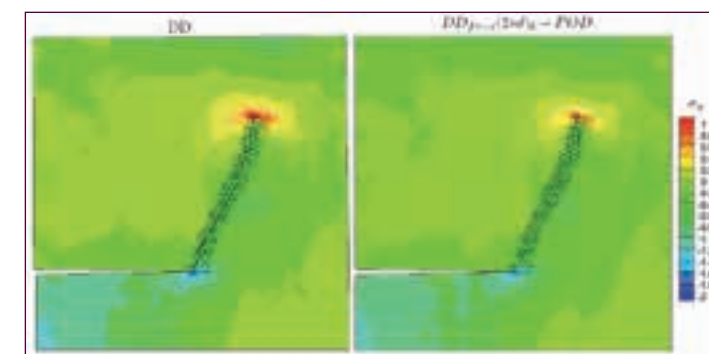
2. Kalthoff's experiment: maps of . Comparison among the outcomes of the reference DD approach and of the reduced methodology.

PIEZOELECTRIC VIBRATION MICRO ENERGY HARVESTERS

Giacomo Gafforelli - Supervisor: **Alberto Corigliano, Raffaele Ardito**

Co-Supervisor: **Sang-Gook Kim**

In recent years the world is facing an extraordinary diffusion of the "Internet of Things" (IOT) concept which is the idea of building smart and autonomous sensors networks that help us in sensing, understanding and controlling our environment. For this idea to be effective, new sensors should be small, barely costless and autonomous. Recent advances in low-power consumption circuitry have enabled ultra-small power integrated circuits which can run with extremely low amount of power. This scaling trend has opened the door for on-chip energy harvesting solutions, eliminating the need for batteries or complex wiring, thus forming the foundation for battery-less autonomous sensors networks which can harvest on-site the energy they require for their operations.

Piezoelectric MicroElectroMechanical Systems (MEMS) energy harvesting is an attractive technology for harvesting small amount of energy from ambient vibrations. This work presents current developments in this technology and studies i) cantilever, ii) bridge-shaped and iii) frequency up converter harvesters in order to highlight advantages and drawbacks of each solution. The major innovative contributions proposed in this thesis are:

· Developing a refined, yet simple model with the aim of providing fast and insightful solutions to the multi-physics problem of energy harvesting via piezoelectric layered structures. The main result has been to retain a simple structural model (Euler-Bernoulli beam), with the inclusion of effects connected to the actual three-dimensional shape of the device. Numerical validation of the model has been performed.
· Developing a model for piezoelectric bridge-shaped harvesters which properly includes nonlinear stretching strain and piezoelectric coupling. The main result has been to show that the power generation of resonant energy harvesters is bounded by the mechanical damping. However, nonlinear resonant harvesters have much wider power bandwidth and achieve lower displacements than that of linear resonators. Experimental validation of the model has been performed.
· Proposing and designing a simple and efficient frequency up conversion mechanism that allows for MEMS scale integration and it is fully compatible with microfabrication processes.

SELF- HEALING CAPACITY OF CEMENTITIOUS COMPOSITES

Visar Krelani - Supervisor: **Prof. Liberato Ferrara**
Co-supervisor: **Prof. Romildo D. Toledo Filho**

The self- healing capacity of cementitious composites employed for either new or repairing applications opens challenging perspectives for the use of construction materials intrinsically able to recover its pristine durability levels, thus guaranteeing a longer service life of the designed applications and a performance less sensitive to environmental induced degradation. One possibility of achieving the aforementioned self-healing capacity stands in the use of additives featuring a "delayed crystalline" activity. These additives are able, when in contact with water or atmosphere humidity, to form chemical compounds which are able to reseal the cracks thus guaranteeing the recovery of a pristine level of mechanical performance.

In order to approach the investigation, besides conventional concrete (with and without the aforementioned admixtures) the characterization of the self-healing capacity of High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) with steel fibers and combination with the natural ones was also studied, i.e. their capacity to completely or partially re-seal cracks, as a function of the material composition, maximum crack opening and exposure conditions. This also implies

a new structure concept and a wider worthiness of the sustainability of engineering applications which can be achieved thanks to the use of high performance cement based materials, which encompasses and overcomes the traditional one related to the use of by-products in mix-compositions, which can be effectively pursued also in this case

In order to quantify this self-healing ability and its effects on the recovery of mechanical properties a methodology has been developed and validated in the thesis. It consisted in pre-cracking up to different crack opening levels (a three point bending scheme with COD measurement was employed) prismatic beam specimens, made with both concrete, with or without the aforementioned additive. Moreover, for HPFRCCs, the topic has been investigated including the effect of different flow-induced alignment of fibers, triggered through tailored casting, which can result into a material exhibiting either a strain hardening or softening behavior, whether stressed parallel or perpendicularly to the fibers. In all cases, specimens were initially pre-cracked, according to a 4-point bending scheme, and up to different values of crack openings. Specimens were then submitted to different "conditioning

environment" (natural winter or summer environment, water immersion, exposure to humid or dry air, wet-and-dry cycles, representative temperature and humidity cycles representative of winter and summer exposure) for different exposure times. After scheduled exposure durations the specimens were tested up to failure according to the same scheme employed for pre-cracking and results, in terms of load-crack opening curves were compared to those obtained from virgin specimens before any "treatment". Dedicated microscopic investigation completed the experimental program and allowed to have a deeper insight into the true nature of the crack healing products and hence of the self-healing mechanism. The significant amount of garnered experimental results also allowed suitable self-healing indices to be defined and quantified, as from the measured recovery of mechanical properties, including load bearing capacity, ductility and stiffness; a predictive numerical approach was also formulated and validated for NSC: this is a much needed approach in order to consistently consider the self-healing phenomenon into a durability based design.
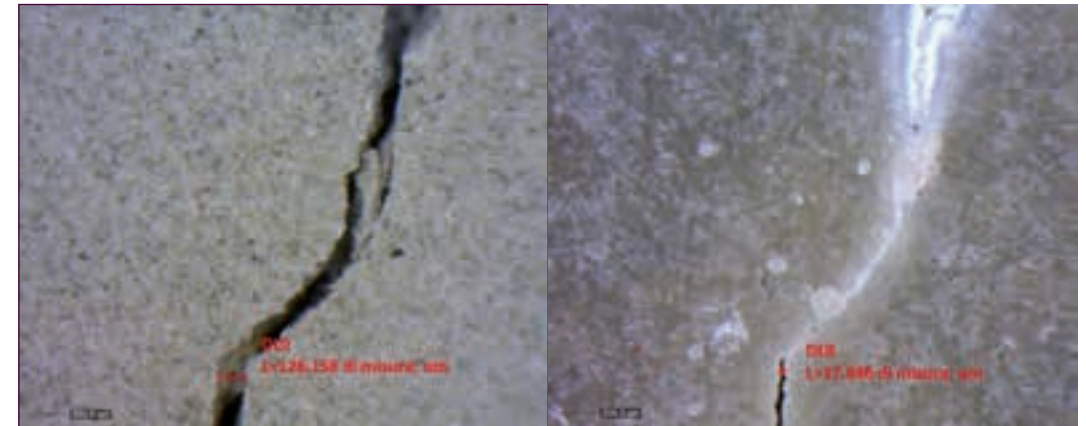
1. Healed crack for specimen (a) pre-cracked up to 100 μm; (b) 1 month of water immersion

2.Healed crack for specimen (a) pre-cracked up to 150 μm; (b) 6 months of water immersion
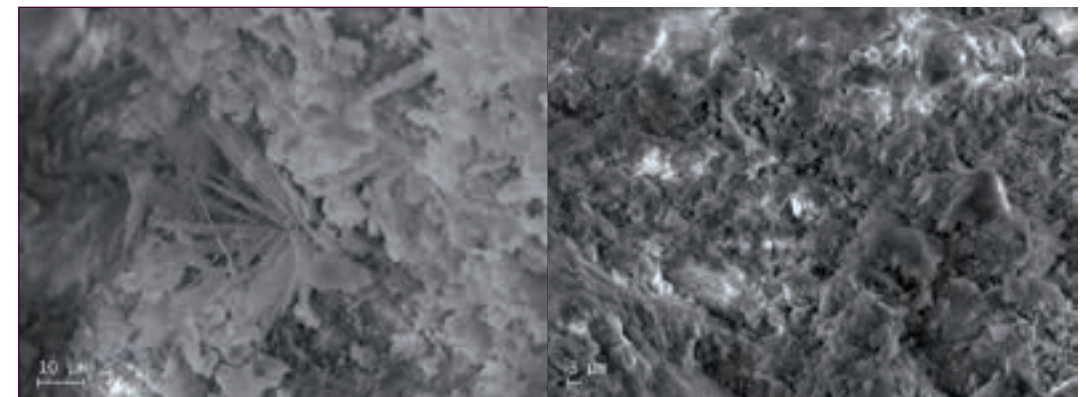
3. SEM image inside the surface of healed crack (a) magnification up to 10 μm; (b) magnification up to 3 μm for specimens immersed in water after 6 months

THE CONTROL OF MULTIPOTENCY AND DIFFERENTIATION OF STEM CELLS IN THREE-DIMENSIONAL SCAFFOLDS STRUCTURALLY INTERACTING AT THE CELL SCALE

Michele Nava - Supervisor: **Manuela T. Raimondi**

The control of stem cell response in vitro, including multipotency maintenance and lineage commitment, has been proved to be directed by mechanical cues, even in the absence of biochemical stimuli. Through focal adhesions, cells are able to anchor, sense and react to the surrounding microenvironment. Mechanical factors, including the substrate stiffness, the surface nanotopography, the microgeometry, and extracellular forces can all have significant influence on regulating stem cell activities.

To provide an interpretation of how mechanical cues can be used to direct stem cells fate in vitro, we introduced the concept of "force isotropy" relevant to cytoskeletal forces and relevant to extracellular loads acting on cells. This notion allowed to quantitative interpret the experimental results relevant to the advanced culture substrate fabricated via two-photon laser polymerization technique. During two-photon polymerization (2PP), a tightly focused femtosecond laser pulse induces a crosslinking photoreaction in the polymer confined within the focal volume. As a rapid-prototyping technique, 2PP enables the fabrication of truly arbitrary three-dimensional (3D) micro- and nanostructures directly from computer models, with a spatial resolution down to 100 nm. For these reasons, 2PP fabrication represents the suitable technique to create scaffolds mimicking the native 3D environment in which cells reside.

We applied 2PP to fabricate 3D microscaffolds, or "niches", to study rat and human mesenchymal stem cells (MSCs) response to mechanical cues. The main advantage of this study model is that it allows to directly compare, on the same sample, significantly different culture configurations and, therefore, different levels of cytoskeletal tension and nuclear spreading. We used a hybrid organic-inorganic photoresist called SZ2080. The niches, of sizes fitting in a volume of 100×100×100 μm^3, were made by an external containment grid of horizontal parallel elements and by an internal 3D lattice. We developed two niche heights, 20 and 80-100 μm, and four lattice pore dimensions (10, 20, 30 μm and graded). We used primary rat MSCs to study cell viability, migration and proliferation in the niches, up to 6 culture days. MSCs preferentially stayed on/ in the structures once they ran into them through random migration from the surrounding flat surface, invaded those with a lattice pore dimension greater than 10 μm, and adhered to the internal lattice while the cell nuclei acquired a roundish morphology.

In the niches, the highest MSC density was found in those areas where proliferation was observed, corresponding to the regions where the scaffold surface density available for cell adhesion was the highest. The microgeometry inducing the highest cell density was 20 μm high with graded pores, in which cell invasion was favored in the central region of large porosity and cell adhesion was favored in the lateral regions of high scaffold surface density. Cell density in the niches, 17±6 cells/ (100×100 μm^2), did not significantly differ from that of the flat surface colonies. This implies that MSCs spontaneously homed and established colonies within the 3D niches.

We improved the synthetic niche system to study the effect of mechano-topological parameters on morphology, renewal and differentiation of rat MSCs. Niches arranged in complex patterns were formed in a photoresist with low auto-fluorescence, which enabled the clear visualization of the fluorescence emission of the markers used for biological diagnostics within the internal niche structure. The niches were structurally stable in culture up to three weeks. At three weeks of expansion in the niches, cell density increased by almost 10-fold and was 67% greater than in monolayer culture. Evidence of lineage commitment was observed in monolayer culture surrounding the structural niches, and within cell aggregates, but not inside the niches. Thus, structural niches were able not only to direct stem cell homing and colony formation, but also to guide aggregate formation, providing increased surface-to-volume ratios and space for stem cells to adhere and renew, respectively. Then, to give more conclusive evidence of multipotency maintenance within niches, we increased the number of engineered niches from 7 to around 400 niches per sample, covering 10% of the available culture surface, in the aim to obtain larger niche-cultured cell numbers of around 8000 cells per sample, compared to the average 140 niche-cultured cells per sample available in our previous investigations. We cultured human bone marrow derived MSCs for three weeks on the improved synthetic niche culture system. Despite the weaknesses of the improved synthetic niche culture system, we demonstrated that cells cultured on 2PP-written substrates maintained both the proliferation potential and the bilineage differentiation potential more effectively than cells cultured on standard two-dimensional (2D) culture surfaces where spontaneous lineage commitment occurred.

We performed experiments for functionalizing the niche surface with a suitable coating with tailored mechanical properties, to further control cell adhesion. We have demonstrated an effective methodology to control the surface stiffness of engineered 3D scaffolds for stem cell culture. We found that the presence of the coating significantly influences the cell behavior and commitment inside the niches. Work is in progress to discern the roles of the different cues (physical and chemical) in determining the cell behavior in the coated substrates. Nevertheless, this first study introduces a new and powerful platform to investigate the synergistic effects of the 3D microarchitecture and of tailored surface mechanical properties. Since we observed a greater multipotency and differentiation potential for rat and human MSCs cultured on the advanced niche culture substrate compared to cells cultured on standard flat glass substrates, we addressed these differences to the distinct adhesive configuration that cells show in culture in the synthetic niche substrate. Indeed, significantly different culture configurations and, therefore, different levels of nuclear spreading (e.g. distinct cytoskeleton tensional states), were observed. By processing confocal image sequences, we measured and quantified distinct levels of spreading relevant to each nuclei. Significant differences in nuclear surface, volume and shape were found according to the cell localization in the synthetic niche substrate. According to these data, we set-up a computational multiphysics model aiming to give a modeling interpretation of the experimental results. The computational model describes how the diffusive mass transport of transcription factors across the nuclear envelope is influenced by nuclear deformation. A simple relation describing the diffusivity as a function of the deformation couples the two phenomena. Computational results showed that in spread nuclei, the strain-dependent diffusivity amplifies and accelerates the nuclear import of transcription factors if compared to roundish nuclei. This outcome supports experimental evidences on the pivotal role played in nuclear spreading and mechanics in cell functions. Despite several limitations, the computational model is quite innovative to our best knowledge. It allows explaining the functional differences we observed in the experiments and supports the role of cell-substrate interactions as a primary stimulus involved in stem cell fate determination. In conclusion, this experimental and computational study brings to light the crucial role played by the 3D microarchitecture effects on MSCs fate in culture, with potential implications for the design of biomaterial scaffolds for synthetic niche engineering.

STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

GEOTECHNICAL AND MODELING ISSUES IN THE DESIGN OF SETTLEMENT REDUCING PILES FOR HIGH-RISE BUILDINGS

Fabio Tradigo - Relatore: **prof. Claudio Giulio di Prisco**

In everyday engineering practice, piles are often designed by neglecting load redistribution over the raft and the underlying piles, as if piles alone were resisting all the loads coming from the superstructure. This disregards the fruitful use of piles in combination with the raft to reduce average and differential settlements induced by service loads. In this context, Piled Rafts (PR) and Disconnected Piled Rafts (DPR) are to be distinguished, depending on whether the piles are structurally connected to the raft (Fig.1). DPR setups are characterized by no pile-raft structural connection and by a pile/raft gap which is usually filled with a layer of compacted granular material.

Owing to this latter, the loads coming from the superstructure are not directly applied on the piles, so that the design of DPR foundations is no longer driven by cumbersome structural requirements - which is at variance with PR. From a design perspective, the adoption of DPR also leads to admit lower safety factors for the piles.

The mechanical response of these foundational systems results from complex soil–structure interaction mechanisms, whose analysis and interpretation are still under discussion within the technical community. Improving the insight into such interaction phenomena is preliminary to optimal design and, therefore, to an efficient use of piles in the engineering practice. Because of the intrinsic complexity of the raft-soil-pile mechanical interaction, resorting to three-dimensional finite element analyses seems to be the most reliable option, since complex geometries and material non-linearity can be naturally taken into account. The suitability of FE analyses is even more evident in the case of DPRs, where less intuitive raft-soil-pile interactions are expected to take place. While simplified methods for PR design have been widely studied, the lack of any analogous study in the literature for DPRs makes the use of numerical analyses mandatory in all practical cases.

In the context of numerical approaches, a few FE parametric studies on DPRs have been presented to investigate the influence of different geometrical/mechanical factors, such as the cushion stiffness, the gap and the raft thickness and the overall piling configuration. Nonetheless, the need for reliable and well-established numerical modelling of DPR foundations is still urging, especially from a design perspective. In fact, in case of high-rise buildings the number of piles is so high that the computational cost of carrying out fully three-dimensional FE analyses would be unbearable even for modern workstations, especially when employing elasto-plastic constitutive models and solid elements. While this issue is usually mitigated in case of PRs by employing the so called "embedded pile" (EP) elements, no studies have been presented in the literature with respect to DPRs.

In this study, preliminary axisymmetric and EP analyses of a single isolated pile are carried out with reference to two in-situ pile load tests in Milan in order clarify the role played by all the involved parameters.
In addition, the soil-structure interaction of a single disconnected pile is studied by carrying out AS elasto-plastic parametric analyses. Analyses lead to propose and validate a new methodology to employ EP elements in DPR configurations.

PRs and DPRs are compared by performing fully three-dimensional elasto-plastic FE analyses. The complex interaction mechanisms involved under purely vertical loads are investigated over a realistic range of raft-soil gaps and for different pile configurations. Particular attention is also devoted to the response of structural members. Moreover, the relevant issues related to the use of EPs for DPRs are tackled, applying the aforementioned methodology to check the consistency between fully solid and EP models.

Finally, the PR foundation of the Isozaki Tower in Milan is numerically simulated and compared with site monitoring results. After the calibration of soil and EP interface models by means of two preliminary and three contract pile load tests, the entire foundation is modelled and its behaviour compared to monitoring results. Finally, the performance of the foundation is studied by inserting a gap layer between the pile heads and the raft, as well as by carrying out analyses of the unpiled foundation.
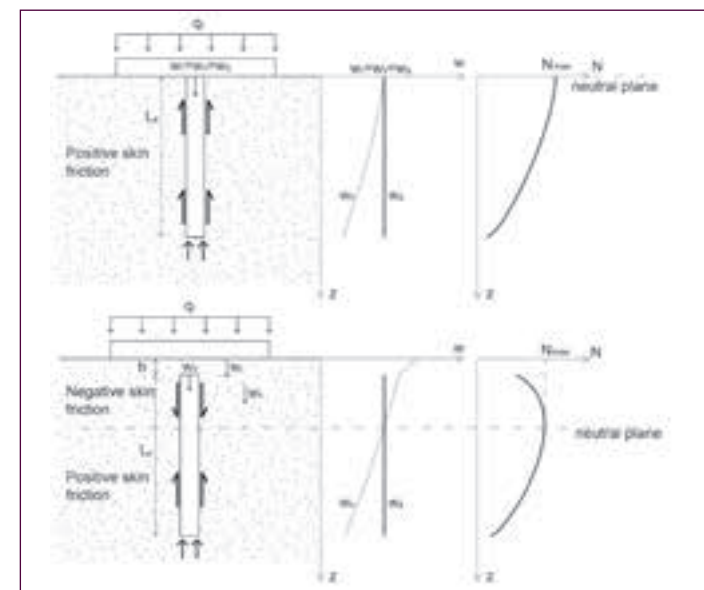
1. Soil-structure interaction in PR and DPR foundations.
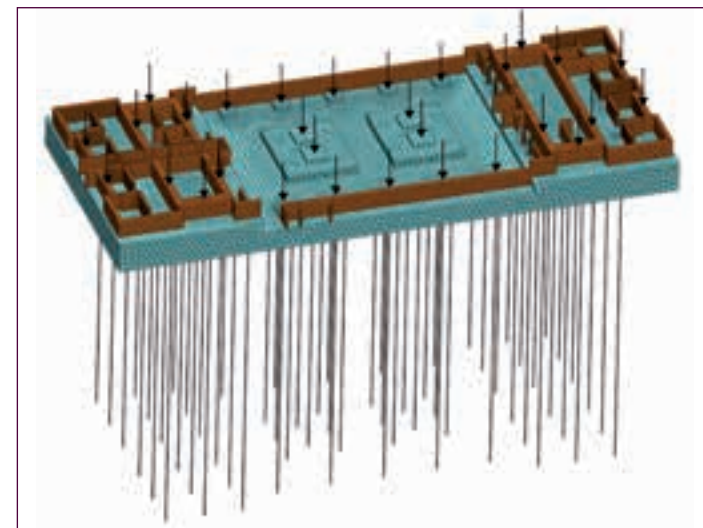
2. Isozaki tower PR foundation FE model.

A MULTIDISCIPLINARY APPROACH FOR THE STRUCTURAL ASSESSMENT OF HISTORICAL CONSTRUCTIONS WITH TIE-RODS

Mira Vasic - Supervisor: **Prof. Carlo Poggi -** Co-supervisor: **Prof. Dario Coronelli**

The present research studies the structural behaviour of historical constructions with tie-rods. Preservation and maintenance of buildings with heritage value include ensuring their sufficient bearing capacity against different loads. This is a challenging task when dealing with historical masonry structures that are characterized with a complex hyperstatic structural system. While currently there are extensive studies on masonry historical structures having no tie-rods as a permanent part of their structure, there is a limited number of studies on Gothic cathedrals with tie-rods where lateral thrusts are resisted by a combined action between tie-rods, spandrels and buttresses. Their analysis is therefore not straightforward because it is difficult to estimate what portion of the thrust is resisted by each of these elements. The thesis proposes how different approaches can be combined towards understanding the structural behaviour of masonry constructions with tie-rods. It also develops a methodology for estimating current state of the stress in such historical structures. In particular, a continuous process of data acquisition, analysis of structural behaviour, diagnosis and safety evaluation was employed for the case study of Milan's

cathedral (Duomo di Milano). This remarkable monument was chosen in the present research due to its multifaceted structural history, imposing dimensions and some structural issues observed at the present. The ancient builders used the tie-rods during the construction. Original tie-rods are still present in both longitudinal and transversal direction of the Duomo di Milano, which makes understanding its structural system challenging. Different techniques and fields of expertise were used for the data acquisition: historical investigation gave important information on the tie-rods origin, their structural purpose and the construction process of the Cathedral; the wide experimental campaign included visual inspection, material characterization, and dynamic tests on the original ties and contributed to the understanding of the structural system. Relevant aspects for the study of the Cathedral's structural behaviour were addressed and various approaches were used, such as the limit analysis and Finite Element Modelling (FEM). The dynamic testing campaign confirmed that the tie-rods in the Duomo di Milano are active members, carrying part of the lateral thrust, as suggested by the historical research and

structural analysis in the present work. Moreover, the axial tensile force was estimated for the largest portion of tie-rods in the Cathedral and was combined with graphic static analysis employing limit analysis for a representative bay of the Cathedral. Graphic static analysis gave one of the possible equilibrium solutions for the structure of the Duomo di Milano. Another solution was found using sophisticate FEM model, which took into account damage in masonry and simulated different construction stages of the Cathedral. Including structural history in the numerical analysis showed to be one of the essential aspects for understanding tie-rod's behaviour in the past and present, so as for producing reliable results. In case of a cathedral with active tie-rods, as the Duomo di Milano, disregarding construction stages could underestimate current stress in the tie-rods for about 50%. The method for combining different approaches used in the present work resulted in understanding the structural system of a cathedral with tie-rods, but developed concepts can be applied to similar hyperstatic structures.