



## DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:

**Prof. Roberto Paolucci**

### 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 both basic issues and engineering applications. As a consequence, great attention is given

to many fundamental topics still highly-debated within the scientific community, and to many application-oriented topics, that are of direct interest for the public and private industry, for the designers and for the institutions dealing with structural safety and reliability, and with the environmental impact of the structures.

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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# LIFETIME PERFORMANCE AND SEISMIC RESILIENCE OF CONCRETE STRUCTURES EXPOSED TO CORROSION

Elena Camnasio - Supervisor: Prof. Fabio Biondini

Structural systems suffer aging, fatigue and deterioration over lifetime. Depending on the environmental exposure, aggressive chemical attacks and other physical damage mechanisms affect the structural performance by altering the material and mechanical properties. The effects over time of these complex phenomena depend on both the type of damage process and the structural scheme. In fact, the local damage at element level is reflected at global level by a time-variant structural response under service loadings or accidental actions and others extreme events, such as earthquakes.

The evaluation of the condition of existing structures and infrastructures gained increasing attention over the past decade. Huge stocks of buildings, bridges, roads, railways, dams, ports and other construction facilities have been rated showing significant deterioration and structural deficiencies. Moreover, maintenance costs have a considerably high economic impact. For example, the ASCE's 2013 *Report Card for America's Infrastructure* assessed that an increased investment of about \$10 billion annually is needed to improve the condition of the nation's bridge network by repair interventions, without considering indirect economic

losses.

European and Italian design codes and standards recently included specific requirements related to the durability of reinforced concrete structures in the perspective of lifetime extension. In particular, requirements for concrete cover, water/cement ratio, minimum cement content, amount and type of cement, among others, are established depending on environmental exposure, in order to limit concrete degradation and steel corrosion. However, the current prescriptive approach discards the interactions between the parts of the structure and the environment. Current codes limit the checking of strength requirements at local analysis, without explicitly considering for the interaction between the structural system, the load conditions and the environmental exposure. Actually, a durability failure may be a partial reason for mechanical failure. In this perspective, significant research advances have been accomplished recently in the fields of modeling, analysis and design of deteriorating Civil Engineering systems. These advances highlighted the need of incorporating life-cycle concepts in a global design approach to account for the effects of deterioration processes on the overall structural

performance. Moreover, a reliable assessment of the performance of structures over time has to be carried out in probabilistic terms, because of the uncertainty in material and geometrical properties, in the physical models of the deterioration process, and in the mechanical and environmental stressors.

A reliable design combined to a proper maintenance planning may improve the long-term performance of structures under environmental deterioration and time-variant loadings, thus reducing life-cycle costs. The importance of a performance-based design of new structures and the need of repair interventions of existing deteriorated structures are also emphasized by the recent growth of associations such as IABMAS (International Association of Bridge Maintenance and Safety, founded 1999) and IALCCE (International Association for Life-Cycle Civil Engineering, founded 2006).

In particular, engineering interest has increased in the evaluation of safety and serviceability of reinforced concrete structures in earthquake-prone regions. Current time-invariant capacity criteria do not account for the increased vulnerability to seismic hazard of deteriorating structural systems, due to corrosion-

induced damage of both concrete and reinforcing steel. However, the progressive decay of the mechanical properties of corroded concrete members may lead at global level to a variation of the resisting hierarchy and to a shift in the failure mode. While the strength capacity is mainly related to the corrosion of the steel bars, the impacts on the overall stiffness and system ductility are associated with others mechanisms, such as a reduced confinement and bond deterioration between concrete and reinforcing steel.

These considerations emphasize the importance of new generation design procedures in which the structural behavior is related to both the seismic intensity level and the environmental aggressiveness. A proper calibration of the design objectives and limit states should be planned in order to ensure suitable levels of performance and safety over the required structural lifetime. In particular, when aging and deterioration are considered, the evaluation of the system performance should account for additional probabilistic indicators aimed to provide a comprehensive description of the lifetime seismic resources.

Due to their disruption potential for communities and infrastructures, earthquakes represent a dominant hazard. After catastrophic events, such as the Loma Prieta Earthquake in 1989 and the Northridge Earthquake in 1994, risk assessments and mitigation programs have been carried out in the attempt to reduce future losses and post-disasters recovery costs. Under these circumstances, the concept

of seismic resilience emerged as the capability of a system, a community or a society, to withstand the effects of extreme events and to recover efficiently the original performance and functionality.

Resilience of critical facilities, such as hospitals and infrastructure networks, has been investigated with reference to damage and disruption caused by seismic events. However, for structural systems damage could also arise progressively in time due to environmental aggressiveness. Consequently, the functionality loss at the occurrence of a seismic event of same magnitude may vary over lifetime due to the time-variant structural functionality, thus implying a reduced system resilience. The time-evolution of the actual functionality state of structures exposed to corrosion should then be considered in order to effectively assess and possibly enhance the lifetime resilience.

In such context, this Thesis presents a probabilistic approach to lifetime assessment of seismic performance and resilience of concrete structures under corrosion considering the mutual interaction of seismic and environmental hazards. The proposed approach is based on a general methodology for the analysis of deteriorating structures over time. A review of criteria and methods for environmental damage modeling and life-cycle analysis of concrete structures is presented. Measures and indices for the evaluation of seismic damage are discussed in order to identify suitable performance indicators of the lifetime structural

behavior. The general approach for lifetime seismic reliability analysis under uncertainty is presented, as well as criteria and methods for a time-variant measure of the seismic resilience of deteriorating structures.

The role of the environmental damage on seismic resilience is investigated by comparing the system functionality in the original state, in which the structure is intact, and in a perturbed state, in which a damage scenario is applied. The time-variant seismic capacity associated to different limit states, from damage limitation up to collapse, is assumed as functionality indicator, and seismic resilience is evaluated with respect to this indicator over the structural lifetime.

The influence of recovery interventions and target functionality is also investigated by means of efficiency coefficients.

The effectiveness of the proposed procedure for the lifetime assessment of concrete structures is shown through applications, including a multi-story frame and a continuous bridge. The results show that structures designed for the same functionality target may exhibit over time different seismic performance and resilience depending on the environmental exposure. This highlights the need of a life-cycle oriented seismic design approach and the importance of a lifetime resilience assessment in a perspective of risk mitigation.

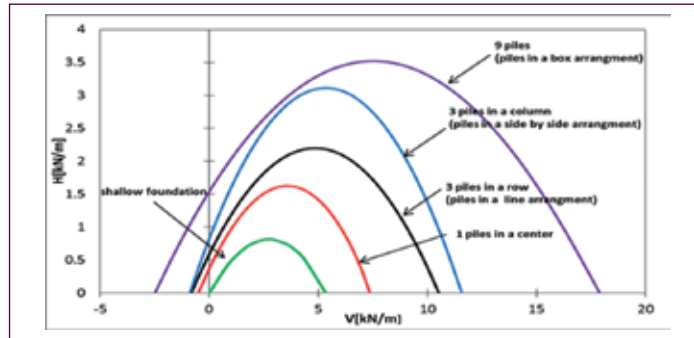
# NON-LINEAR SOIL-FOUNDATION INTERACTION UNDER CYCLIC LOADING

Iman Farshchi - Supervisor: Dr. Andrea Galli & Prof. Francesco Calvetti

Many cyclic loads of different nature may affect the civil and environmental structures, such as wind effect, sea-wave actions and earthquake. From the geotechnical point of view these extreme and complex loading paths can cause large irrecoverable and plastic deformation in the soil, which can cause damage to the structure or even its complete collapse. It is then evident the importance of studying effects of cyclic loads even in the case of post-yielding behavior for both soil and foundation, but empirical data are still far from sufficient, to develop a reliable interpolative numerical model. This thesis deals with soil-foundation interaction by considering both shallow and deep foundation under cyclic loads. The work is divided into three parts:

## 1- Experimental works:

This part has been performed by means of a small scale experimental set up capable of applying cyclic or monotonic, horizontal and vertical loads. The experimental works is sub-divided into three parts, referred to shallow foundation, shallow foundation plus piles and deep foundation interacting with a loose sand deposit. The tests were performed with the aims of (i) defining the failure condition of the system, (ii) describing the coupling between



1. Comparison of the failure loci obtained analytically for different foundation configuration

horizontal and vertical directions during monotonic tests, and (iii) analyzing the cyclic behavior of the system.

## 2- Mechanical Interpretation by Using the Macro-Element:

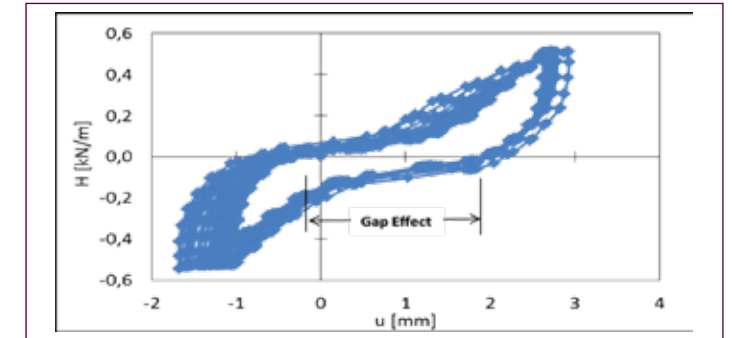
A Soil-foundation interaction approach is employed by applying the macro-element concept. The original macro-element formula for shallow foundation was generalized for the case of shallow foundation plus piles and deep foundation, according to the best fitting to the experimental results (Figure 1). By studying the kinematic of the system, it was also quantified the non-associativeness of the flow rule.

A deep investigation on the response to several cyclic loading paths, combining vertical and horizontal loads, will be presented. In case of cyclic

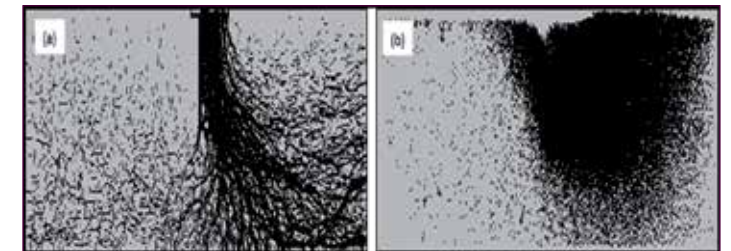
symmetric tests, the shape of the cycles in the case of using deep foundation, illustrate sort of gap effect (Figure 2). This phenomenon in the granular materials is due to a volume of reduced stiffness zone around the pile lateral surface. The experimental results will be interpreted in particular in terms of the average stiffness and of the damped energy of each cycle, as well as the accumulation of permanent displacements during cycling. A clear increase in stiffness and decay in dissipated energy will be observed after applying number of cycles, and influence of the loading path and the type of the foundation has been studied.

**3- The numerical analysis:** For this purpose, the Distinct Element Method (*DEM*) has found to be a helpful numerical model for simulating the microstructure of

the geo-materials. This method provides a synthetic material that can be used to understand how the microstructure affects the macroscopic behavior. In this part the aim is to simulate the soil-foundation behavior quantitatively and qualitatively under the monotonic and cyclic loading. It could be observed that, although the numerical model shows a good qualitative performance (for instance ratcheting phenomena in cyclic tests), but elastic stiffness regarding to the numerical results was way too large. The interaction between the balls and the foundation had to be considered to overcome this problem. In fact the dominant factor is the ratio of the mean grain size of the balls to the characteristic size of the structure. If the size of the foundation itself compared with the size of the balls was large enough to have a sufficient number of balls in contact with the foundation, this problem can be progressively overcome. *DEM* simulations also provided clear overview of the failure mechanisms developed within the sand (Figure 3).



2. Load-displacement curve for the cyclic symmetric test



3. PFC3D results (a) distribution of contact force for inclined loading (b) displacement increment for inclined loading

# REINFORCED CONCRETE IN FIRE: FROM MATERIALS BEHAVIOUR TO SPALLING SENSITIVITY AND STRUCTURAL MODELLING

Francesco Lo Monte - Supervisors: Pietro G. Gambarova, Roberto Felicetti

The increasing use of High-Performance Concrete in many of the structures exposed to extreme environmental conditions (tunnels, off-shore platforms, Liquefied Natural Gas terminals, containment shells), and the need to repair/strengthen many existing structures in order to meet the most recent code provisions or to increase their useful life (e.g. nuclear power plants), bring in new problems, which go beyond the excellent knowledge we have on the behavior of ordinary concrete in extreme conditions. In the specific case of high temperature, which also includes fire with its very high heating rates, at least two topics need to be further investigated: (a) concrete hot mechanical behavior, and (b) concrete spalling, which consists in the more or less explosive and extended expulsion of concrete pieces due to thermal stresses and vapor pressure in the pores. The second topic mainly concerns High-Performance Concretes. These cementitious materials, in fact, on the one hand have denser matrices (which ensure better durability and mechanical properties, at the cost of greater brittleness and sensitivity to high temperature), on the other hand justify the optimization of the mix design in terms of aggregates, fibers and other

constituents.

High-Performance Concretes are definitely promising, but their behavior in fire denotes a greater sensitivity to heating, mostly because of their denser matrix. As a matter of fact, the ensuing lower porosity and - even more - the lower permeability are advantageous in ordinary environmental conditions (because concrete durability is improved), but bring in higher pore pressures due to water vaporization, because the release of vapor pressure is impaired by the lower permeability (so, making these concretes very sensitive to spalling). Generally speaking, the study of R/C structures exposed to high temperature requires the solution of a hygro-thermo-mechanical problem with many facets: (a) concrete microstructure (porosity and permeability, water saturation and fluid transfer, all strictly related to the development of pore pressure); (b) concrete thermal properties (whose knowledge is instrumental in evaluating the in-time evolution of the thermal field in any structural member); and (c) the mechanical behavior of the materials (in compression and tension) and how it is affected by high temperature and pore pressure. Dealing with a hygro-thermo-

mechanical problem as such, however, is no simple matter and often goes beyond the objective of structural engineering. Hence, a possible approach is to treat the thermo-mechanical problem separately from the hygro-thermal problem. In this way, the first step is to investigate the hot mechanical response of the materials as such and within the structural context, neglecting the spalling phenomenon (i.e. the hygral problem); once the thermo-mechanical behavior is known, specific experimental and numerical studies make it possible to optimize the concrete mix design in order to limit or avoid spalling. Starting from the above mentioned issues, the present research project aims to contribute to the knowledge of cementitious materials and structures in three main directions:

- definition of a numerical procedure for the static analysis of R/C structures exposed to fire (thermo-mechanical problem), by using and comparing a number of constitutive models available in the literature, in order to numerically modeling full-scale tests on columns;
- development of an experimental method to assess concrete sensitivity to spalling, and evaluation of the pore pressure due to high

temperature;

- understanding of the influence of pore pressure on the hot tensile behavior of concrete, for different concrete grades and aggregate types, with/without polymeric fibers.

Concrete mechanical behavior at high temperature is made increasingly complex because of the nonlinearity induced by further temperature-related strain components, like the thermal creep and transient strains (which are mostly irreversible and occur only during the first heating). These temperature-related load-induced strains makes concrete response definitely less stiff, and bring in a relaxation of the self-stresses (which is generally advantageous) and an increase of second-order effects (detrimental to members stability). These somewhat contradictory aspects require nonlinear structural analyses to be performed, but introducing properly concrete kinematic properties at high temperature is no easy matter, as experimentation to evaluate thermal creep and transient strains is rather complex. (For instance, transient tests with the temperature increasing under sustained loads are required). Hence, a thorough and critical study of the concrete constitutive models available in the literature is mandatory, to check - through systematic applications to well-documented structural cases - the efficacy of each model and to understand whether certain parameters play a minor role and may be neglected, to simplify the models or to identify the most effective model, as the best compromise in terms of fitting the test results

and numerical handiness. An ad hoc software has been developed by using Fortran and GID as Pre- and Post-Processors; fifty-five R/C columns tested in the laboratories of the Technical University of Braunschweig (39 tests; Hass, 1986) and of the University of Ghent (16 tests; Dotreppe et al., 1996) were modelled numerically, and the time to failure was calculated according to four models, taking into account second-order effects. The systematic study performed and documented in this project allows to clarify and understand (a) the relevance of the different approaches to model thermal creep and transient strains, implicitly or explicitly; and (b) the role of second-order effects. As already mentioned, the hygral problem (evaluation of pore pressure) is not introduced in this first step of analysis (so, spalling is neglected). Spalling phenomena, however, strongly affect the fire resistance of most structural members, because of the ensuing reduction of the cross sections and - in most cases - of the exposure of the reinforcement to the flames. However, in spite of the many studies performed in the last twenty years on spalling, to what extent pore pressure may affect concrete tensile behavior is still not totally understood. To contribute to a better understanding of pore pressure-tensile strength connection, an innovative technique has been developed at the Politecnico di Milano and two experimental investigations have been carried out on different classes of concrete ( $f_c = 40, 60$  and  $90$  MPa), with three types of aggregate (natural mixed/

calcareous/basalt aggregate), with or without polymeric/metallic fibers; one concrete mix and eleven concrete mixes were investigated in the first and in the second experimental campaign, respectively. Testing has been accompanied by numerical modeling in order to study the role of the thermal stresses (induced by the restrained thermal dilation). The first experimental campaign was focused on the optimization of the testing procedure, and on the roles of both thermal stresses and heating rates, while the second more comprehensive experimental campaign was aimed at understanding firstly how pore pressure may affect concrete behavior in tension and secondly what is the role (if any) of concrete grade, aggregate type, and fiber type and content. The experimental results give fresh - and largely new - information on: (a) concrete tensile behavior, that is strongly affected by pore pressure; and (b) the role of aggregate type, as well as that of fiber type and content, on pore pressure, this role being substantial in modifying the interaction between pore pressure and concrete behavior in tension. This information is instrumental in understanding spalling phenomena, with the aim of giving cement producers, designers and contractors the tools necessary to improve the fire performance of R/C structures.

# MECHANICS OF STRETCHABLE INTERCONNECTS FOR STRETCHABLE ELECTRONICS DEVICES

Riccardo Lucchini - Supervisors: Pasquale Vena

In the PhD thesis, a research on the mechanics of stretchable electronic device has been carried out. Classical microelectronic systems are basically rigid or at best mechanically flexible, limiting the applications in different fields characterized by the request of conformable shape and by the ability to withstand large deformation. Stretchable electronics is the newest field of research within the topic of the large-area electronics, which has seen a growing interest over the last decade.

Stretchability is a mechanical feature, which is usually achieved by coupling micron-size electronic devices with a polymer-based stretchable substrate; electrical current is carried by interconnects which have to be stretchable as well. Stretchable electronics devices can undergo large and reversible deformation; given the intrinsic low compliance of the sensing electronic, the stretchability of the whole device is granted by the elastically deformed interconnects.

Several approaches have been developed with the purpose to realize elastically stretchable interconnects. Among others, conductive elastomers or polymer/metal and polymer/CNT nanocomposites have been proposed. However, the electrical conductivities

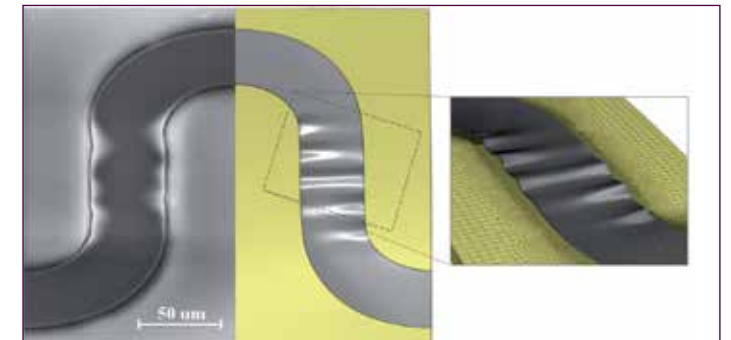
achieved through the above approaches are often insufficient for electrical interconnects and still not comparable with that achieved through metal conductive lines. The use of metal films becomes straightforward with the development of co-planar patterned conductors: the conductive material is patterned onto an intrinsically elastic substrate (i.e. polymer) with a reliable design essential to keep the structural integrity during extreme deformations. Since large strain are involved and reliability under cyclic loads can be a functional request, two main limits represents critical aspects in the stretchable electronics interconnects: i) the occurrence of interface failure phenomena in interconnects subjected to high deformation ii) the mechanical reliability of the metal line loads at the transitions between flexible (the rigid sensor islands) and stretchable parts (the interconnects).

The above two aspects have been studied in the present work at two different scale respectively through: i)  $1\mu\text{m}$  thin aluminum interconnects deposited on  $10\mu\text{m}$  stretchable polyimide substrate and ii)  $17\mu\text{m}$  Copper interconnects embedded in 1mm Polydimethylsiloxane (PDMS) stretchable substrate.

## Interface Failure

Stretching-induced delamination, with the development of cohesive and adhesive fracture, is one of the major factors limiting the capability to achieve large deformation for a given interconnect. An ad hoc mechanical testing and suitable cohesive modeling have been developed. In particular, a micro-tensile testing with simultaneous imaging of the samples has been carried out by means of a suitably developed micro-tensile equipment. Optical and ESEM observations have been obtained during stretching of the interconnects. A quantitative study of the deformation mechanisms involving delamination and buckling of the metal conductive lines was achieved. The mechanical tests have been simulated through finite element modeling integrated with a cohesive approach able to explicitly account for the delamination phenomena. The submodeling technique has been also applied with the purpose to gain detailed information on small size area around the metal/polymer interface and to achieve a sufficient mesh refinement with reduced computational effort. A global model, able to represent the sample behavior exploiting periodic boundary conditions

has been used to determine displacement-based boundary conditions to local, and more refined, models focusing on the interface. The traction vector acting at the cohesive surface modeling the interface between the metal and polymer layers has been derived from the interfacial potential proposed by Xu and Needleman. The original formulation have been suitably modified in order to account for three-dimensional problems; furthermore, additional modifications has been introduced with the purpose to model a loading-unloading asymmetric response and to account for mixed-mode delamination. Shear and normal tractions components have been considered as functions of the normal and tangential opening. The cohesive mixed-mode formulation yielded delamination morphologies which were consistent with that observed in the experiments, thus establishing the importance of irreversible and coupled normal-tangential behavior, a comparison with the ESEM image is reported in figure 1. The numerical model turned out to be a suitable tool to predict the mechanical response of such a kind of metal/polymer interconnects and to identify the role played by the geometrical features. This makes the numerical model, developed



1. Comparison of the delamination, white areas, morphologies from ESEM experiments (on the left) and from the computational model (in the middle). A detailed view of the adopted mesh is also reported (on the right)

in the present work, as a good candidate as a design tool.

## Mechanical Reliability

In order to understand the effect of the flex-stretch transition on the mechanical reliability the cyclic behaviour of  $17\mu\text{m}$  thick copper interconnections with four different geometries embedded in 1 mm PDMS encapsulation have been studied with fatigue cyclic tests at 10% of elongation. The stretchable interconnections are composed of few meanders anchored between flexible regions. Numerical models that simulate the mechanical behavior of the copper-based interconnects have been developed based on the submodeling technique, to focus the computational effort on the most critical regions of the metal lines. The fatigue life of all designs has

been evaluated and mutually compared on the basis of the accumulation of plastic strain. Mechanical characterization of the constituent materials have been carried out, at the real scale, by using the nanoindentation technique and micro-tensile tests for the copper and tensile tests for the PDMS. A good correlation between the model and the experiments allowed to establish a fatigue life prediction by using the Coffin and Manson relationship between the accumulated plastic strain obtained through the models and the experimental meander life. On the basis of the above life prediction model, a new design has been proposed for a copper based interconnects which will exhibit a longer fatigue life.

# BEHAVIOUR OF COUPLING BEAMS RETROFITTED WITH ADVANCED CEMENTITIOUS COMPOSITES: EXPERIMENTS AND MODELLING

Milot Muhaxheri - Supervisor: Marco di Prisco, Liberato Ferrara

Fibre reinforced cement based composites due to their enhanced mechanical performance, mainly for their peculiar tensile behaviour, in recent decades have attracted a great attention among research and engineers community as a replacement of conventional concrete or as strengthening/retrofitting solution in existing r/c structures. Usually the lateral resistance of medium and high rise buildings relies on r/c concrete core, which due to architectural restraints such as door or window opening their compact integrity is break down, resulting on structural division into singular shafts which usually are connected with deep beams so called coupling beams. In order to provide a good transfer a forces between the shafts these beams should be properly designed, which require a dense and complicated reinforcement arrangement. In this thesis it is explored the use of fibre reinforced cement based composites as upgrading/retrofitting solution for the poorly designed coupling beams, namely the High Performance Cementitious Composite (HPFRCC) and Textile Reinforced Cementitious Composite (TRCC). This has involved a "multiscale" studies which started from material characterization and moved up to structural element and to the structural level.

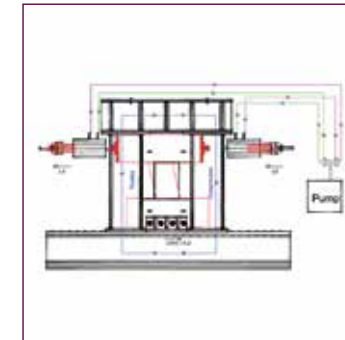
In order to design the experimental test specimens reference has been made to the case of a shear wall containing a typical door opening 900 mm wide (equal to the length of the coupling beam) and 2.1 m high; this resulted (assuming the inter-storey height equal to 2.7 m) in a depth of coupling beam equal to 600 mm and hence in a span to depth ratio of 1.5. The coupling beam was perceived to be a "poorly designed" element; just satisfying the minimum reinforcement requirement prescribed by design codes for non seismic design situations. Previously calibrated numerical approach based on multi fibre Timoshenko beam element was used for estimation of load bearing capacity of coupling beams with different strengthening typologies. The experimental campaign performed involved tests on "non retrofitted" coupling beam specimens, through which it was possible to study the influence of the different resisting contributions (concrete tensile strength, longitudinal and transversal reinforcement), as well tests on retrofitted ones. Two retrofiting choices were pursued: with HPFRCC (6 specimens) and TRCC (2 specimens), tested both under monotonic and reversed cyclic displacements. In total 14 specimens were tested.

In order to have an insight into the results of the experimental results at member level a through characterization of the retrofiting material had also to be performed. A newly conceived test method known as Double Edge Wedge Splitting for the identification of material tensile behaviour of HPFRCC has been employed. Moreover the fracture toughness parameters were related to fibre density and orientation assessed both through non-destructive and destructive testing technique. Depending on the fibre orientation either a strain hardening or softening behaviour can be obtained. Constitutive laws were proposed in tension for both cases and have been implemented in "crush-crack" damage model. The same numerical model used for modelling DEWS specimens, has been then applied to model the behaviour of HPFRCC coupling beams under monotonic loading, making reference to the experimental campaign performed at University of Michigan on 4 individual coupling beams, cast with either conventional reinforced concrete or HPFRCCs and with different reinforcement arrangements. As a further step, an alternative modelling technique was explored using a multi fibre Timoshenko beam element,

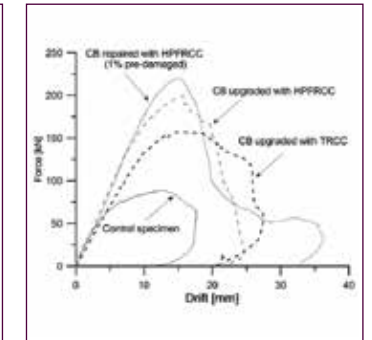
which incorporates reliable description of unilateral effects of concrete cyclic behaviour, in which suitable assumptions resulting from the previous modelling phase were also incorporated. This approach has been then adopted to predict the cyclic behaviour of coupling beams made of or retrofitted with HPFRCCs and provided reliable description.

Based on maximum load estimated the testing frame setup was designed as shown in (Figure 1). A testing setup also consisted of two jacks with maximum load capacity of 400 kN and stroke length of 200 mm, have been used to apply the load to the specimen. A hydraulic pump is used with a control panel directly connected to the jacks to generate the pressure in piston of the jack. The pump has two sets of inlet and outlet of the oil; for our purpose was sufficient only one valve. Through two extensions and four tubes it has been possible to create a closed loop of oil flow between the two jacks. This system allowed to effectively implement and apply to the specimen a cyclic loading path with two jacks counter acting each other, as illustrated in (Figure 1).

A synopsis of the most significant results is provided in (Figure 2) of the monotonic performance of coupling beams



1. Schematic representation of the testing setup



2. Comparison of the experimental evidences under monotonic loading considering different strengthening/retrofitting techniques

with different strengthening/retrofitting typologies, difference between the curve relative to the control coupling beam and the others has been remarkable, especially in terms of load-bearing capacity. From the coupling beam strengthened with HPFRCC it is obtained a load capacity of 199 kN, whereas for the case of repaired coupling beam with HPFRCC (under 1% monotonic pre damage) the maximum load recorded was 220 kN. The load capacity with respect to the control beam is respectively 2.27 and 2.5 times. In the coupling beams upgraded with TRCC a significant increase in load capacity is observed reaching 156 kN, 1.77 times higher with respect to the control coupling beam.

Finally the results performed

were employed to numerically assess the efficacy of coupling beams retrofiting on the structural performance of a shear wall. The efficiency of the HPFRCC retrofiting of a poorly designed coupling beam in recovering the same coupling action as a correctly designed one has been highlighted. The possibility of retrofiting coupling beam at selected lactations along the wall height with equal structural performance was also addressed through a numerical parametric study.

## FORMABILITY OF A NON-CRIMP 3D ORTHOGONAL WEAVE E-GLASS COMPOSITE REINFORCEMENT

Juan Francisco Pazmino Flores - Supervisor: Prof. Valter Carvelli, Prof. Stepan V. Lomov

In this dissertation, the formability of a single layer E-glass non-crimp 3D orthogonal woven reinforcement, is experimentally and numerically investigated. The aim of this research is to study the deformability of the 3D woven reinforcement, in order to predict its behavior during shaping process; and to validate the obtained numerical simulations with experimental results.

The motivation that led my research to focus our attention on the formability of 3D composite reinforcements is the importance of experimental analyses and numerical simulations of draping process, to determine the conditions for a successful manufacturing of composite a preform.

First the state-of-the-art in forming processes of textile reinforcements for composites is presented. The literature review includes a description of the experimental techniques currently used to study the deformation mechanisms involved during draping, as well as a summary of the experimental investigations and numerical simulations of forming performed on two- and three- dimensional textile reinforcements. Afterwards, the main features of the material studied in this dissertation are detailed. The production

process of the 3D fabric and the studies carried out from 2005 up to date on the non-crimp 3D woven reinforcement and composite, are illustrated.

The central part of this work focuses on the experiments carried out to study the formability of the non-crimp 3D orthogonal weave E-glass composite reinforcement.

The experimental campaign includes: (i) the mechanical characterization of the 3D fabric by uniaxial and biaxial tensile, bias extension, picture frame, bending, transverse compression, and transverse shear testing ; (ii) an investigation at the unit cell level of the internal deformed geometry of the reinforcement by X-ray micro-CT observations; (iii) measurements of the fabric thickness variation during shearing by laser registrations; and (iv) formability tests of the 3D reinforcement on two complex shapes, i.e. tetrahedral and double-dome. In addition, a comparison between two different digital image correlation software programs, namely VIC-3D and MatchID3D, used to measure the deformation during shaping processes of the reinforcement, is reported.

Finally, the results of finite element simulations obtained with the continuous hyperelastic constitutive model adopted

in this research are illustrated.

The material model is described and validated by comparing the predicted mechanical behavior with experimental results.

Tetrahedron and double-dome case studies are simulated and local deformations are compared with experiments.

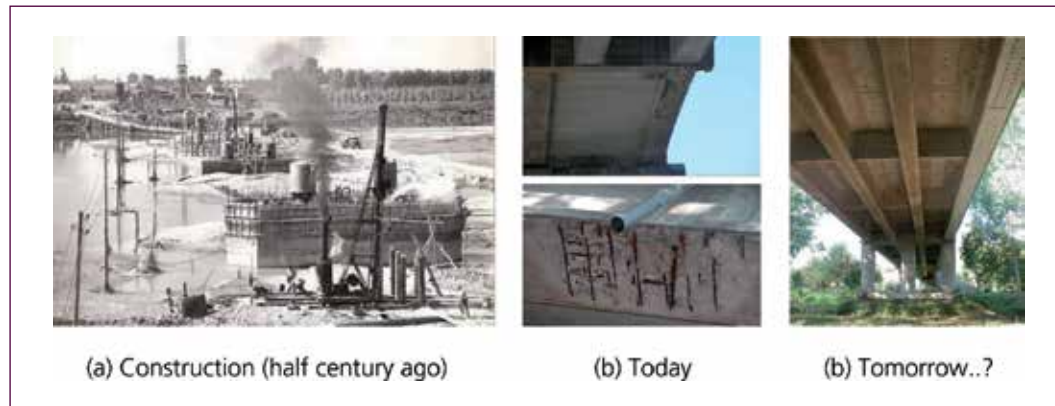
The obtained experimental results give an extensive knowledge on the mechanical behavior, internal deformed geometry and formability of the considered 3D composite reinforcement. Moreover, agreement between experimental results and numerical simulations for tetrahedron and double-dome draping processes demonstrated the capability of the adopted continuous hyperelastic constitutive model to predict the behavior of the non-crimp 3D orthogonal woven reinforcement during forming processes.

The Doctoral Thesis is carried out in a collaboration framework among Politecnico di Milano (Italy), Katholieke Universiteit Leuven (Belgium), and Institut National des Sciences Appliquées de Lyon (France).

The material considered in this dissertation is produced and commercialized under trademark 3WEAVE® by 3Tex Inc. (USA).

# FROM BIDIMENSIONAL TOWARDS MONODIMENSIONAL MODELING OF SOUND AND DAMAGED REINFORCED CONCRETE STRUCTURES

Manuel Quagliaroli - Supervisor: Prof. Pier Giorgio Malerba



1. Life steps of a bridge over the Po River, Italy.

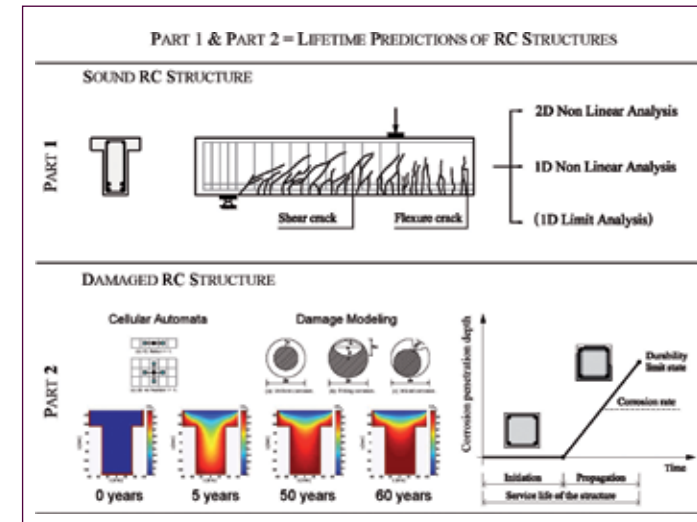
The majority of buildings and infrastructures, like bridges, has today reached more than an half of a century of age. In a research carried out for the Lombardia Region (Italy), in which the Author collaborate, the bridges that across the Po River have been inspected. The main result of such a research is that today, a lot of structures are reaching their ultimate lifetime. Damage scenarios, like corrosion due to chlorides, spalling of the concrete cover, reduction of area of reinforcing, are clearly evident. In some case, a repair intervention is already present, Fig. 1. Region ask questions such as: what about the future of these bridges? Are they safe? How much are they safe? And if they are not, what we can do? The answers to these

questions are not so simple as the questions are.

The phenomena involved in damage processes are not so clear and, in addition, not so certain due to dependability on aleatory quantities such as the humidity of the air, the chlorides content and so on. Hence, a robust assessment of concrete structures based on time-variant capacity that account for environmental hazards is needed.

The object of the thesis is to propose a methodology that can be applied in engineering practice in order to couple the structural analysis with the damage processes, and able to adequately evaluate the time-evolution of the structural performances.

All the phenomena that characterize the mechanical behavior are dealt with. The thesis is identified by two big parts: (1) dedicated to the study of sound Reinforced Concrete structures. From bidimensional modeling, the objective is to move towards monodimensional modeling by including shear's effects; (2) dedicated to the study of the damage processes interesting Reinforced Concrete structures exposed to environmental hazard. In the first part, a new shear-flexible beam column element has been proposed, in the second part all the corrosion effects interesting Reinforced Concrete structures have been modeled by a special evolutionary technique called Cellular Automata.



2. Bending Stress of Tunnel Top-Position at the Mid-Span in Elastic and Inelastic Models under Earthquake

The complete proposed methodology is illustrated in Fig. 2.

A wide set of applications confirm the soundness of both of theoretic proposals and of the algorithms used to reduce the problems to algebraic forms. The types of application stand out the effectiveness of the model in dealing with actual and complex structures.



# INTRINSIC DAMAGE AND SPALLING SENSITIVITY OF CONCRETE SUBJECTED TO HIGH TEMPERATURE

Chiara Rossino - Supervisor: Prof. Pietro G. Gambarova

After a comprehensive analysis of the relevance of social and economical aspects related to the problem of concrete structures exposed to high temperature/fire (in the following: thermal actions, T. A.), a literature review is reported with the aim to introduce the state of the art on this subject. From this review, it arises that many efforts have been devoted to investigate the effect of T.A. on mechanical properties of concrete, as well as the chemo-physical reactions (C.F.R.) occurring in cement pastes. On the other hand, a relatively low number of studies have been focused on the relationships between the C.F.R. of the basic concrete constituents and the resulting concrete mechanical properties. The knowledge of these relationships may result also in a useful tool for design appropriate concrete mixes able to resist to T.A. For this reason, an extensive collaboration between CTG-Italcementi Group and Politecnico di Milano (DICA) has been activated to perform a joint research project, with the main scope of investigating:

- the relationships between the intrinsic damage, due to C.F.R. and thermal incompatibility between cementitious matrix (C.M.) and aggregates, and the consequent mechanical properties;

- the thermo-mechanical damage deriving from vapour pressure build-up in concrete, attributable to the onset of temperature gradients with time and space.

The experimental part was performed on 11 concrete mixes ( $f_{cm,cube} \geq 45, 70, 95$  MPa), formulated under the following restraints:

- same slump class (S5, according to EN 206) and type of cement (CEM I 42.5 R);
  - same volume fraction of the cement paste.
- The following mix parameters were considered:
- mineralogical nature of the aggregate;
  - type of the fibers (polymer, either monofilament and fibrillated, and steel);
  - fiber content.

## Mechanical and microstructural characterization:

the compressive strength, the secant elastic modulus (MES) and the spitting tensile strength were determined according to European Standards. The mechanical characterization was completed with the acquisition of constitutive law ( $\sigma$ - $\epsilon$ ) in compression according to internal test method. The chemo-physical characterization was focused on both the chemical composition (by

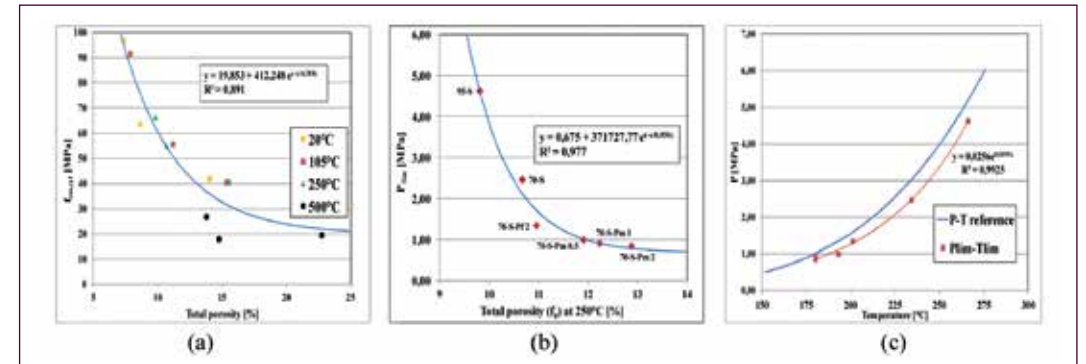
X-Ray Diffraction -XRD- and Thermogravimetric Analysis -TGA) and the microstructure (by Mercury Intrusion Porosimetry -MIP- and Scanning Electron Microscopy -SEM). Maximum pressure build-up ( $P_{lim}$ ) and temperature ( $T_{lim}$ ) at failure and the thermal diffusivity, both during monotonic heating, were evaluated as well, by using the specific test procedures developed by DICA.

## Thermal cycle:

the concrete specimens were subjected to a single thermal cycle (TC) at different "reference" temperatures ( $T_{max} = 105, 250, 500$  and  $750^\circ\text{C}$ ). The residual properties were compared with those obtained at  $20^\circ\text{C}$ .

## Results:

XRD indicates that two main thermal degradation processes take place: dehydration and decarbonation, both quantitatively assessed using TGA. SEM observations allowed monitor the crack pattern evolution at increasing  $T_{max}$ . Cracking usually started at the aggregate-cement paste interface, propagated into C.M. and finally bridged the aggregates. In the case of basalt concrete (B), this evolution was strongly limited, even at  $T_{max} = 750^\circ\text{C}$ , and only few thin cracks



1. (a) Compressive strength vs.  $f_p$ ; (b)  $P_{lim}$  vs.  $f_p$  at  $250^\circ\text{C}$ ; and (c)  $P_{lim}$  vs.  $T_{lim}$ .

were observed. In calcareous (C) and silico-calcareous (S) concretes, cracks were wider and more diffused; C concrete showed the worst behaviour. The MIP microstructural tests indicate that as  $T_{max}$  increases, the total porosity ( $f_p$ ) increases and  $f_{cm,cyl}$  exhibits a typical exponential decay (Tab.1(a));  $P_{lim}$  (vs.  $f_p$ ) behaves similarly (Tab.1(b)). The voids left free by polymer fibers (detectable by MIP) caused a dramatic decrease in  $P_{lim}$  above  $500^\circ\text{C}$ . The results concerning the compressive strength and MES showed decay trends vs.  $T_{max}$  that confirmed values found by other Researchers. Thermal diffusivity data ranges B, S and C concretes; B showed the lowest.

## Discussion and conclusive remarks:

the MIP results allowed to justify the exponential decay law by identifying a critical range of pore radius responsible for the sizable differences in  $P_{lim}$  of mixes having almost the same  $f_p$  (after T.A.) but different  $f_{cm,cube}$ . Coupling MIP and SEM results allowed to identify the

appearance of microcracks, whose size is similar to that of macropores ( $>10\mu\text{m}$ ). From these observations, B concrete exhibited less microcracking compared with S and C ones, after T.C. This microstructural behavior was in some way reflected by the different post-peak behaviors of the  $\sigma$ - $\epsilon$  curves. In fact, MIP and SEM observations indicated that at  $T_{max} = 500^\circ\text{C}$ , B concrete is affected by very thin microcracks, this being associated with the steeper post-peak branch than in either S and C mixes ( $f_{cm,cube} \geq 70$  MPa).

Concerning spalling-related phenomena during monotonic heating, MIP results were used to determine the bound water released into the pore system and the moisture specific volume ( $V_{sp}$ ). In this way the pressure P values corresponding to the measured temperatures  $T_{lim}$  were identified in Clapeyron's plane (P- $V_{sp}$ ). A satisfactory agreement was found between the experimental values ( $P_{lim}$  and  $T_{lim}$ ) and those derivable from Clapeyron's plane (Tab.1(c)). Through this procedure, known

the relationships  $P_{lim}$ - $f_p$  and  $V_{sp}$ - $f_p$ , it's possible to identify the thermodynamic state (P,T, $V_{sp}$ ) of the moisture at any assigned temperature value  $<T_{lim}$  and then to evaluate the ratio between P and  $P_{lim}$  ("risk of failure"). Porosity  $f_p$  affects also the thermal diffusivity, for the same mineralogical nature of the aggregate, as well as the type of aggregate.

All the microstructural observations turned out to be instrumental in understanding the decay phenomena, describable by a generalized exponential law, and the mechanism that induce the pressure build-up in heat-exposed concrete.

# THE INFLUENCE OF CARDIAC TRABECULAE ON VENTRICULAR MECHANICS

Marta Serrani - Supervisor: Prof.ssa M.L. Costantino

## Introduction

In the adult heart, cardiac trabeculae are cylindrical structures which cover the inner surfaces of both ventricles. They are characterized by an axial orientation of cardiac fibres and are arranged in a complex shape, preferably oriented along the ventricular apico-basal direction. The trabecular mass represents a significant percentage of the ventricular total mass; in healthy subjects, this percentage has been estimated to vary from 12 to 17% of the total ventricular muscular mass. Even if there is not a universally accepted criteria, a value of trabecular mass higher than 20% of ventricular mass is considered an index of pathology. In spite of this evidence, the literature lacks of quantitative information about the trabecular network architecture and the hypotheses about the possible functions of trabeculae are mainly just speculations. The aim of this work is to understand the influence of ventricular trabeculae on cardiac performances.

## Methodology

To understand the role of cardiac trabeculae on heart mechanics, a finite element model of the left ventricle was developed with Abaqus (Abaqus®, SIMULIA Corp.). In particular, the purpose

was to compare the ventricular behaviour in the presence or in the absence of the trabecular non-compact layer. Two different geometries were implemented: a "smooth" and a trabeculated model. In both cases, the left ventricle was simplified as a truncated ellipsoid. To design the reference trabeculated geometry, the 15% of the total muscle mass was changed from compact layer to trabeculae at the endocardium. The trabeculae were described as cylindrical strands oriented along the ventricular axis direction, laying onto the endocardium (Fig.1).

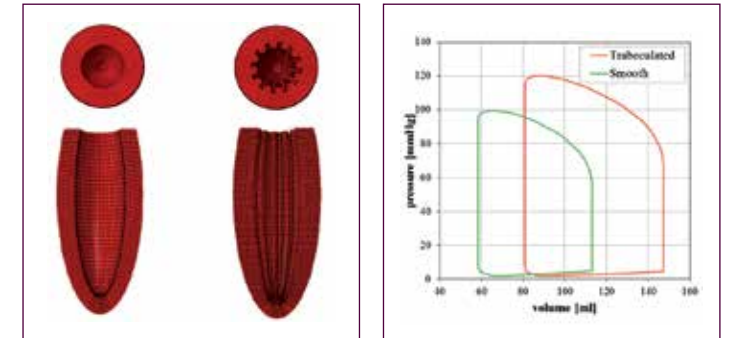
Further, the trabeculae diameter, mass and orientation were changed in the trabeculated model to investigate the influence of these parameters on the model outcomes. For comparison purpose, the intra-ventricular volume and the total ventricular muscular mass were kept constant in all the models. Two major features were considered while modelling the cardiac tissue behaviour to obtain a realistic response: the peculiar myocytes arrangement in the ventricular wall and the constitutive relationship to simulate the myocardium mechanical behaviour. The ventricle is characterized by a complex three-dimensional helical architecture of the myocytes.

In fact, the left ventricular wall is composed of discrete layers of parallel myocytes with a variable orientation across the ventricular wall: in the compact layer, the preferential fibres direction is about  $-80^\circ$  near the epicardium, rotates to  $0^\circ$  at the midwall and reaches  $+80^\circ$  at the endocardium with respect to circumferential direction; in the non-compact layer the fibres follow the trabecular axial direction. To replicate this fibre arrangement, a different orientation of fibres was assigned at every "sheet" which composes the compact part of the ventricular models using a custom algorithm. In the trabeculated model, the fibres were oriented axially in the trabeculae. About the mechanical modelling of the cardiac tissue, both the passive and the active material behaviour were implemented. The passive tissue response was modelled by an anisotropic hyperelastic constitutive law. The material parameters were optimized by fitting the physiologic pressure-volume relationship of the ventricle during the diastole. The muscle contraction was simulated by changing the material stiffness during the systole; this stiffening was obtained through a material parameters variation which follows the curve of force generated by a cardiac fibre

secondary to an intracellular calcium variation. Further, suitable boundary conditions were applied to the ventricular model. In particular, the boundary conditions included: kinematic constraints to avoid rigid motions of the structure; the implementation of a pre and an afterload circuit to model the presence of the atrium and of the systemic circulation respectively. About the kinematic boundary conditions, all the displacements of the ventricular base were prevented, while the pre and afterload circuit consist of adequate lumped parameters circuits. The preload circuit is a resistance placed between a node representing the left atrium and the ventricle, while the afterload is represented by a RCR circuit. The presence of a fluid at a uniform pressure in the ventricle and the lumped parameters circuits were implemented using hydrostatic fluid elements.

## Discussions

The simulation results show a significant difference in the ventricular hemodynamic if the trabeculae are present. The trabeculated model is characterized by an higher compliance with respect to the "smooth" model. As a result, the ventricular cardiac output at 75 bpm is 5 l/min for the trabeculated ventricle and 4 l/



1. Smooth (left) and trabeculated (right) ventricle.

2. Ventricular PV loops.

min for the smooth ventricle (Fig.2). Besides, the end-diastolic volume increase with the trabecular mass, while an influence of the trabeculae diameter on the fibre stress distribution was found. The ventricular filling is a fundamental parameter in heart functioning; more than the 50% of the patients suffering of heart failure symptoms show a normal ejection fraction and are referred to as diastolic heart failure patients. Moreover, diastolic dysfunctions can be recognized also in patients with systolic heart failure. In this context, the trabeculae can play a fundamental role, since they significantly contribute to the achievement of a physiologic end-diastolic volume and, consequently, a physiologic cardiac output.

Moreover, a possible influence of the trabeculated layer on ventricular energetic was found by analysing the ventricular efficiency. The latter is defined as the ratio between the ventricular work and the myocardial oxygen consumption. Even if a standard method to assess the cardiac oxygen uptake doesn't exist yet, a correlation between the cardiac frequency and the ventricular oxygen consumption was found in the literature. Thus, since the trabeculated model is able to guarantee a physiologic cardiac output at lower heart rate with respect to the smooth model, suggest further studies to investigate a possible enhanced ventricular efficiency determined by the presence of trabeculae at the endocardium are suggested by these results.

# OPTICAL MECHANICAL AND BIOCHEMICAL CHARACTERIZATION OF TRABECULAR BONE

Grazia Spatafora - Supervisors: Prof. Federica Boschetti

Bone is a very complex tissue; changes in composition and properties from molecular scale to organ level arise from the complexity of its structure. Age and pathological conditions influence bone response both mechanically and optically. The most common bone pathology is osteoporosis. Several treatments are available for osteoporosis, but no reliable methods are available to diagnose it at the early stage. The research is moving towards the development of new techniques able to non-invasively assess the conditions of bone and to detect changes in composition and/or structure in the very early phase of the pathology development. The knowledge of optic-mechanical correlation will be used to increase our understanding of the roles of components in the mechanical characteristics and to develop a non-invasive diagnostic tool for early detection of lesions and/or pathological conditions. The present work aims at providing novel information about optic, biochemical and mechanical properties of trabecular bone, with a special goal to increase our knowledge of the capability of diffuse optical spectroscopy (DOS) to characterize. Pathological human (56 samples from 12 patients who

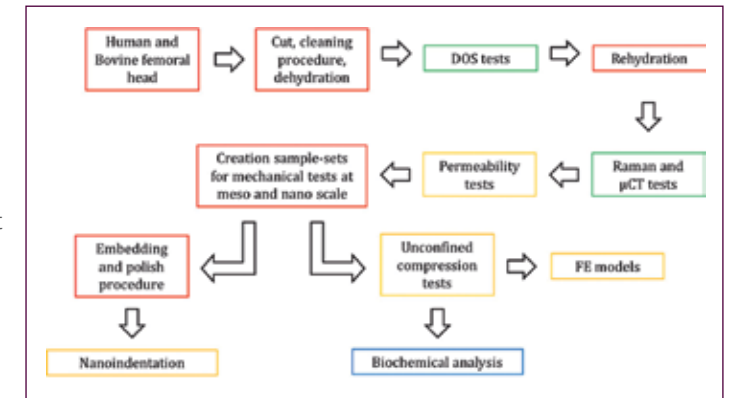
underwent arthroplasty of the hip) and healthy bovine femoral bone samples (10 samples from 5 healthy animals) are analyzed using several techniques. Optical properties are evaluated using Raman spectroscopy, DOS and  $\mu$ CT acquisitions. Briefly, Raman spectroscopy returns information about the bone composition in terms of mineralization and cristallinity, estimating the relative content of organic and inorganic parts in the bone matrix;  $\mu$ CT images completely characterize bone structure using typical morphometric parameters and permit the reconstruction of a virtual 3D model of each sample and DOS returns information about both of the composition and the structure at the mesoscale. DOS works in near infrared range in which scattering events dominated the optical response of the tissue and, consequently, the main advance of DOS is its capability to penetrate the tissue of several centimeters. Experimental measurements are combined with mathematical model able to describe the transport of the light in the tissue and to increase the sensitivity of the system improving its capability in the detection of alterations. The combination of experimental measurements with a mathematical model

permits to measure the bulk absorption ( $\mu_a$ ) and the reduced scattering ( $\mu_s'$ ) properties. When the light is injected in the tissue only a small part is reflected off the surface, photons tend to propagate randomly inside the tissue and they may be absorbed or scattered. Basically, DOS returns a macroscopic average of absorption and scattering properties that are an indication of quantitative and qualitative composition and structure of every material tested. Mechanical properties of trabecular bone are dependent on the amount of matrix, its composition and structure. Pathological conditions change these characteristics and, consequently, the mechanical response. Mechanical behavior is derived from unconfined compression and nanoindentation tests and direct permeability measurements. The mechanical behavior is further investigated by linking nanoscale to mesoscale mechanical properties through sample specific finite element models. Patients' specific geometries are obtained from the  $\mu$ CT images and imported in a model able to reproduce the experimental unconfined compression tests to assess an average value of the trabecular stiffness. Information about the amount

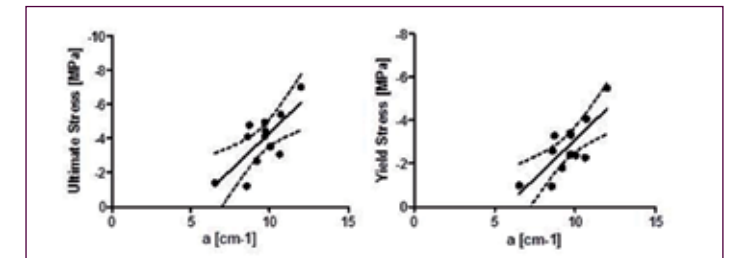
of collagen indirectly evaluated thanks to DOS is compared with results from biochemical tests. The procedure adopted is resumed in figure 1. Lastly, all the data from are compared to determine correlations among the different methodologies, emphasizing the possibility of using DOS information to gather mechanical and biochemical parameters.

This work confirms the connection of mechanical properties with composition and structure evaluated with several techniques. In particular, DOS absorption and scattering spectra give an overview of the mechanical response and return the tissue composition. The most interesting correlations found are between index  $a$ , used to fit the reduced scattering coefficient, and yield and ultimate stresses are statistically significant (figure 2).

In conclusion, the present work provides a complete characterization of trabecular bone from femur and test the capability of DOS for the bone quality evaluation. DOS demonstrate its capability to define the composition and structure of the bone tissue and to use such information to early diagnose osteoporosis at mesoscale. Several correlations are investigated and connected



1. Chronological development of the study: text boxes with red lines describe the samples preparation, green borders the optical techniques, yellow borders the mechanical testing and blue ones the biochemical analysis.



2. Correlation between  $a$  and ultimate stress (left) and yield stress (right).

parameters from DOS system to the mechanical behavior and compositional information are confirmed by biochemical analysis.

Therefore, this study is the first step in the elaboration of a new method to characterize bone tissue and opens the prospective of the development

of a device that will permit a non-invasive analysis to early detect bone pathologies.

# HIGH PERFORMANCE CEMENTITIOUS COMPOSITES FOR SUSTAINABLE ROOFING PANELS

Giulio Zani - Supervisors: Prof. Marco di Prisco

In the last decades, the rapid expansion of the built environment has attracted interest in the development of easy-to-assembly prefabricated components characterized by reliable structural performances, lightness, energy efficiency and durability.

In the design of innovative building systems, High Performance Fiber Reinforced Cementitious Composites (HPFRCC) are becoming increasingly important, since fibers are the easiest way to enhance toughness and ductility of plain materials, fitting the key issue of weight reduction. In this context, this work was focused on the experimental and numerical analysis of thin-walled multilayer concrete panels for roofing applications. The idea was to exploit the potential of sandwich technology by coupling an insulating layer with an outer HPFRCC plate and an inner shell made of Textile Reinforced Concrete (TRC), a combination of fine grained matrices and alkali-resistant glass textiles. In this specific case, it was expected that the coupling of a low stiffness material with concrete layers brittle at the specific level, could give back a lightweight composite panel characterized by multi-cracking phenomena and high inertia. Due to the internal actions

insisting on the horizontal bearing component, the insulating core should ensure an adequate shear transfer, able to keep the TRC layer mainly in tension and the FRC plate mainly in compression. Therefore, different insulating materials were taken into account, so as to guarantee good structural performances during the whole service life. During the program, several experimental tests were carried out, in order to perform the mechanical identification of individual and coupled materials and to develop adequate models for the numerical simulation of the composites. In northern Italy, the interest in the use of HPFRCC has been recently increased due to the need to intervene on existing buildings that do not meet the structural and energy saving requirements imposed by the revised national codes. A retrofitting strategy that might be successfully applied to several precast structures is represented by the substitution of the unsafe tertiary roofing elements with innovative multilayer panels characterized by lightness and remarkable structural performances. The significant self-weight reduction might play a positive role on both the static and the dynamic building behavior, with beneficial effects on

existing load-bearing members such as beams, columns and foundations. The sandwich technology potential can be maximized by coupling the exceptional mechanical characteristics of TRC and HPFRCC with the insulation capability of a thick core layer; this configuration makes lighter structures possible because it fully exploits the materials and, secondly, makes them more environmental friendly because recycled materials can be used. The research aimed at investigating the mechanical behavior of a layered composite structure, designed to achieve the following goals:

- self-weight reduction (70 - 90 Kg/m<sup>2</sup> versus 200 Kg/m<sup>2</sup> of traditional concrete roofing shells);
- global cost reduction;
- exploitation of the shear resistance offered by the insulating cores, generally neglected in the design phase;
- fire safety;
- environmental sustainability, relying both on the improvement of the thermal performances and on the design of Building-Integrated Photovoltaics.

The research was carried out according to the following steps:

- selection of the most promising materials in terms of structural performances, sustainability

and global cost;

- mechanical characterization at the material level, with specific reference to HPFRCC, TRC and insulating cores;
- mechanical characterization of HPFRCC in bending and in uniaxial tension; characterization of TRC in uniaxial tension, at standard and at high temperatures;
- experimental investigation of the bending behavior of Hybrid HPFRCC plates, reinforced with alkali-resistant glass textiles;
- experimental investigation at the meso-scale level, particularly focusing on the coupling of subsequent layers;
- identification of bond-slip relations inherent with the coupling interfaces, by means of push-off tests;
- experimental analysis of the bending behavior of cement-based sandwich composites, produced with different technologies and materials (Fig.1);
- numerical simulation of HPFRCC and development of adequate constitutive laws for the design of sandwich composites by means of non-linear finite element codes.

From the experimental results and the numerical simulations presented in this research, some important conclusions were drawn:

- with reference to HPFRCC, the material was found out to be strongly sensitive towards minor changes in the mix composition. Although the material exhibited significant structural performances, both its strength and ductility turned out to be size dependent. In order to ensure acceptable safety levels concerning with full scale structural



1. Four point bending test on a sandwich specimen

- applications, the size effect of HPFRCC is an issue worthy of further study.
- The low permeability of the HPFRCC composite suggested to prevent the use of a waterproofing layer over the structure. The plates were also characterized by a high fire resistance: if a suitable fixing device is designed to hang the textile thin layer to the upper HPFRCC plate, the empty camera formed with the polystyrene melting becomes an ideal barrier against fire and the TRC panel works as a fire shield preserving the structural bearing resistance of the top plate.
- The main result of this research is the possibility to use layered plates without any special gluing, obtained just using the chemical and mechanical bond strength obtained between polystyrene and high performance mortars. As a matter of fact, polystyrene was considered the most promising material, due to its mechanical behavior, its cheapness and its thermal capabilities.
- The favorable effect of the combination of steel fibers and

glass textile reinforcements on the flexural behavior of thin plates was proved. HyFRCC, in fact, can be successfully applied in precast structures, in order to reduce the dead weights, while increasing the stiffness, the bending resistance and the structural robustness.

- Engineering-oriented numerical simulations can be effectively considered for the determination of the ultimate load and the bending stiffness of sandwich structures. Alternative constitutive relations specifically developed for numerical simulation might have a good potential of application.