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 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.

DOCTORAL PROGRAM BOARD		
Fabio Biondini	Marco Di Prisco	Anna Pandolfi
Gabriella Bolzon	Liberato Ferrara	Roberto Paolucci (Coordinator)
Claudia Comi	Attilio Frangi	Federico Perotti
Alberto Corigliano	Pietro Gambarova	Lorenza Petrini
Claudio Di Prisco	Cristina Jommi	Alberto Taliercio

ADVISORY BOARD	
Luigi Albert (SOIL Geotecnica, Milano)	Giovanna Gabetta (ENI, Milano)
Ettore Anelli (Tenaris, Dalmine)	Guido Mazzà (Enel-RSE)
Carlo Beltrami (Lombardi-Reico Ingegneria, Milano)	Paolo Negro (JRC, Ispra)
Roberto Borsari (Tetra Pak Packaging Solutions S.p.A.)	Silvia Scuri (Artech srl, Milano)
Giovanni Canetta (CeAS, Milano)	Maurizio Teora (Arup Italia)
Stefano Cangiano (C.T.G.-Italcementi)	Massimo Zambon (Techint, Milano)

DYNAMIC MONITORING AND AUTOMATED MODAL IDENTIFICATION OF LARGE STRUCTURES: METHODOLOGICAL ASPECTS AND APPLICATION TO A HISTORIC IRON BRIDGE

Fulvio Busatta - Supervisor: **Carmelo Gentile**

Monitoring, as the observation over time of a state or a condition by the repeated measurement of one or more quantities, is a relatively recent paradigm in the field of Civil Engineering (CE). However, in the last decade, significant progresses, especially in sensing technology, made it possible the installation of many monitoring systems on new and existing CE structures.

Nevertheless, there is, at present, a significant difference between the number of structures equipped with a monitoring system and the number of publications in the literature showing a clear and useful interpretation of the monitoring results, especially when data provided by the technology are used for *Structural Health Monitoring* (SHM) purposes i.e. to inform operators about the health state of a structure and its continued "fitness for purposes".

The engineering motivation for the present dissertation stems from these premises so that a first aim of this thesis is giving a contribution in the field of Monitoring of CE structures: on one hand, developing a general procedure suitable to dynamic monitoring of (large) structures; on the other hand, applying the procedure to a specific case study.

The *San Michele* bridge (1889)

1. Views of the Paderno bridge (1889)

better known as Paderno bridge (Fig. 1) – a historic road and railway iron arch bridge still in service – was assumed as case study since results of dynamic investigations performed in 2009, induced the main institutional owner of the bridge - the Italian Railway Authority (RFI) - to commission Politecnico di Milano the design, installation and management of a continuous dynamic monitoring system (Fig. 2).

In the framework of a dynamic monitoring program, methodologies based on extraction and use of modal parameters to assess the structural state are widely reported in the literature and *Operational Modal Analysis* (OMA) is nowadays considered as a reliable tool for modal identification of systems from experimental data collected in operational conditions.

In the last decades, significant progresses, both concerning test equipments and data acquisition devices, have encouraged the development and the use of this methodology. However, OMA needs to be automated to use it as an "engine" to extract continuously the modal parameters over time, with the "quality" of those extracted, manually, by an expert user. Automation is generally not straightforward since CE structures might exhibit complex dynamic behaviour, conceivably affected by changing environmental conditions.

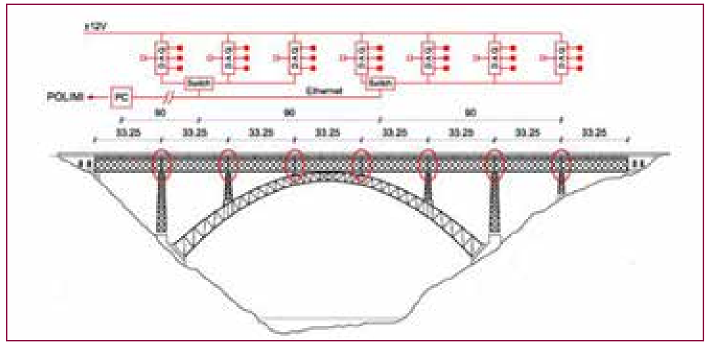
Hence, the development of a reliable, accurate and effective automated OMA procedure is nowadays a major research area.

The technical motivation for this work stems from this second set of premises so that a second aim of the present dissertation is providing a contribution in the field of Automated Modal Identification through the development of an automated procedure based on the Frequency Domain Decomposition (FDD) technique and its application to the data sets collected on a real case (the Paderno bridge).

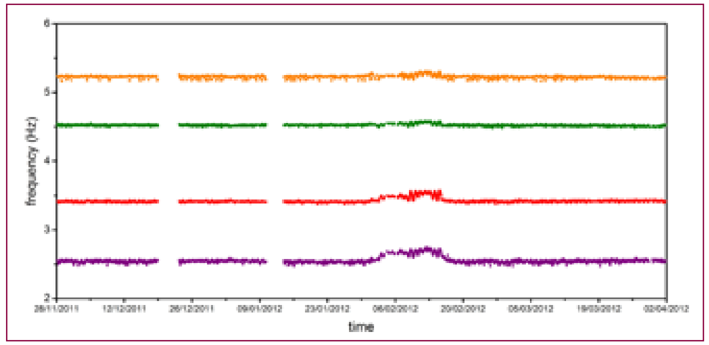
The results obtained show as the automated procedure proposed is generally effective and reliable even when significant variations of the natural frequencies occur due to changing environmental conditions. Results over the first four months of monitoring (November 28th 2011 – April 1st 2012) are firstly shown as tracking of the modal parameters (natural frequencies and mode shapes) and statistics, both concerning the vertical and the lateral modes of the bridge (Fig. 3).

Secondly, possible dependences of the modal parameters on environmental (i.e. temperature) and operational (i.e. road traffic intensity) conditions are investigated. In particular, it was observed as the modal parameters related to the modes that are not significantly affected by temperature can be directly used as control parameters in assessing the structural health state of the bridge whereas, for the other modes, temperature effects should be investigated and removed as long term data will be available.

In conclusion, the permanent dynamic monitoring and automated modal analysis performed on the Paderno bridge have shown to be effective tools for surveying the possible evolution of the bridge structural condition.



2. The monitoring system installed on the bridge



3. Frequency tracking of the first four vertical modes

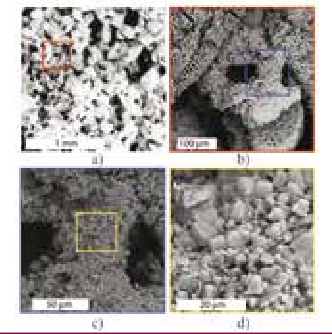
MULTISCALE HYDRO-CHEMO-MECHANICAL MODELING OF THE WEATHERING OF CALCAREOUS ROCKS: AN EXPERIMENTAL, THEORETICAL AND NUMERICAL STUDY

Matteo Oryem Ciantia - Supervisor: **Claudio Giulio di Prisco**

In this thesis the study of hydro-chemo-mechanical effects of weathering on calcarenite, a soft porous rock very common in the Mediterranean regions and in many other coastal areas around the world has been discussed. The comprehension of these processes and their simulation can be, in fact, very useful for (i) conceiving ad hoc experimental tests, (ii) assessing the risk associated with slope and natural cave collapses and (iii) designing new mitigation measures. In particular, the work focused on incorporating hydro-chemical effects, induced by saturation and long term dissolution of a porous rock, into the theory of strain hardening elasto-plasticity. Its main peculiarity is to frame the changes in microstructure in the context of a multi-scale scenario of an array of coupled phenomena. In this way, by means of up-scaling and downscaling procedures, it was possible to reproduce the macro-effects of weathering on the strength and stiffness of calcarenite. In order to reproduce correctly the ad hoc designed weathering tests, the numerical implementation into a finite element based context was necessary. Accordingly, the reactive transport of dissolved ions in a porous rock was also considered and modelled. This allowed to incorporate the dissolution reactions that characterize weathering in a boundary value problem. The obtained results are here below detailed in three (experimental, theoretical and numerical) sections:

Experimental study:

a. In this part the identification of hydro-chemo microstructural mechanisms occurring during the process of wetting in the short term, and during the long term dissolution of calcite that composes the calcarenite structure is approached. This was possible thanks to an accurate and critical microstructural experimental investigation using sophisticated techniques such as dispersive X-ray spectroscopy (EDS), X-ray Micro-Computer-Tomography (MCT), Scanning Electron Microscope (SEM, Figure 1) analyses and Mercury Intrusion Porosimetry (MIP).
b. Mechanical characterisation of the intact and weathered rock by means of standard geomechanical laboratory experimental tests (such as uniaxial, oedometric or triaxial compression tests to name a few) and the transition rock-soil induced by chemical degradation with an ad hoc designed apparatus (such as the Weathering Test Device

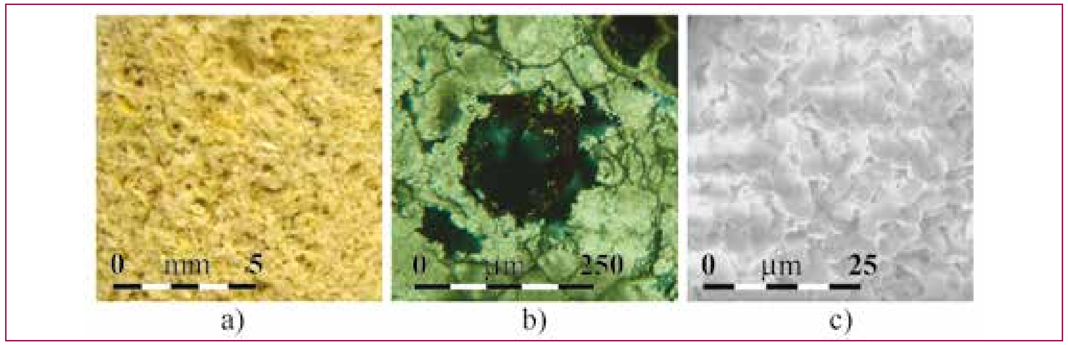


1. SEM images of 3D microstructure with different magnifications: a) calcarenite microfabric, b) calcareous bonds and grains, c) bond structure and d) calcite microcrystals that constitute the bond

under oedometric conditions and the acid controlled creep test). It has been observed that a variation of the stress-strain state occurs without any change in either external load or imposed displacement. The initial rock material, progressively loses its mechanical strength due to the dissolving mass, progressively assuming the typical behaviour of a non-cohesive soil.

Theoretical study:

a. Formulation of a multiscale constitutive model to describe the rate of dissolution of calcite in a stressed configuration. The developing irreversible micro-cracks induce an increase in the specific surface area. As the reaction rate per volume of fluid is proportional to the surface area at the fluid/ solid interface, it follows that the rate evolves with the mechanical damage. In order to develop a numerical model for such a mechanism it is necessary to refer to the scale the mechanism is taking place. To reach predictions at a macro or even regional scale, a multi-



2. Macroscopic view of calcarenite, the soft rock is a porous yellow-whitish stone (macro-scale); b) picture of a macro pore observed through polarized light microscope (meso-scale); c) calcite microcrystals with characteristic length of 5 μm. The whole solid mass is composed by these microcrystals

scale model was developed. The formulation for dissolution and increase in the specific surface area is developed at the micro-scale (Figure 2c), whereas the phenomena of damage described above are formulated at a meso-scale (the size of a macro-pore, Figure 2b). Finally, quantities from these two scales are transferred to the macro-scale level where the continuum mechanics constitutive models are formulated (Figure 2a).
b. A macro scale constitutive model, conceived to describe the material state (stress and strain) variation induced by hydro-chemo processes like weathering. It has been shown as hydro-chemo-mechanical processes can be dealt with in the framework of a suitably formulated elastoplastic strain-hardening theory. The simulations confirm that weathering can be treated as a non-mechanical debonding process. It is also worth noting that the model formulation is general and can be extended to describe other engineering interesting situations in which the variation in the mechanical properties is a consequence of external processes, acting at a constitutive material level (for instance temperature and diagenesis).

Numerical study:

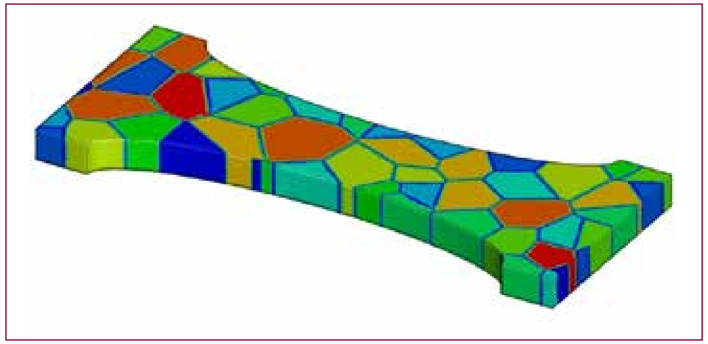
a. The description and modelling of advective diffusive reactive transport of chemical species governing the rate of dissolution of calcite in the finite element method context was fundamental. In fact, the reactive transport of chemical agents induces inevitably inhomogeneity and the time and space evolution of chemically active species is mandatory.
b. Realization of a useful tool for numerical analyses (FEM code) to apply the constitutive model previously defined to boundary value problems. As is shown in the numerical analyses, it has been possible to deal with non-mechanical processes, like acid accelerated dissolution of calcarenite in numerical analyses of small scale boundary value problems. Despite the fact that the case considered is a preliminary study and has deliberately only academic flavour, it shows that the main goal of the work has been reached, since a real problem can be tackled. The model was implemented into a finite element code (GeHoMadrid). The model has been integrated with an implicit algorithm suitable for getting in the linearization procedure the consistent operator in a closed form. As is shown in Chapter 10, both quadratic convergence in the global iteration and high accuracy have been obtained even when non-conventional external loads (as weathering) are imposed. A further innovation of this tool is the possibility of analysing on one side larger scale boundary value problems where weathering was cause of failure and, on the other hand, as a predicting tool since physical time is now a driving variable of the constitutive model.

A DOMAIN DECOMPOSITION APPROACH FOR THE SIMULATION OF FRACTURE PHENOMENA IN POLYCRYSTALLINE MICROSYSTEMS

Federica Confalonieri - Supervisors: **Alberto Corigliano, Alain Combescure**

Microsystems or Micro-Electro-Mechanical-Systems (MEMS) are micro-sized devices combining electronic components with mechanical micro-structures. In many applications they also combine optical, thermal, magnetic or fluidic elements in order to perform a wide range of functions, that can be summarized into the main categories of sensing and acting. Microsystems, like accelerometers, pressure sensors, and gyroscopes, have applications in many engineering field, ranging from the automotive to structural monitoring.

MEMS are often fabricated with polycrystalline silicon (polysilicon); the main reason lie, on one hand, in the fact that fabrication technologies for integrated circuits on silicon wafers can be directly transferred to the manufacturing of micro-sized devices, on the other hand, in the good physical properties of this material. Its average elastic modulus and its strength are comparable to those of steel, while the density is definitively lower; furthermore, polysilicon shows a good resistance to creep; the thermal properties make possible the use of this material also in high temperature applications, as it is characterized by good thermal conductivity, low thermal expansion coefficient and high melting point.



1. Grain morphology of a polysilicon dogbone specimen

Unfortunately, it is to be noticed that polysilicon is a brittle material. This is why the problem of fracture initiation and propagation in this material has to be studied in deep.

Moreover, the always increasing miniaturization of MEMS devices emphasizes the concerns related to the fracture of critical details in microsystems. This is typically the case of failures due to shocks or impacts due to mishandling of the devices containing the microsystems, such as smartphones, laptops, and other consumer electronics products; moreover, other issues need to be addressed at the micro-scale, such as mechanical fatigue. For the aforementioned reasons, the study and the simulation of the dynamic fracture processes in polycrystalline silicon microsystems still deserves attention in the scientific literature.

This work focuses on the micro-scale level, i.e. on the micro-structural parts composing the MEMS device, which may be subjected to local failure phenomena. At this scale, the mechanical behaviour is strongly influenced by the material microstructure and the models have to take into account the presence of heterogeneity, interfaces between grains and micro-cracks. As a result, the polycrystal morphology has to be accurately modelled and a very refined discretization is required to reproduce the grain geometry.

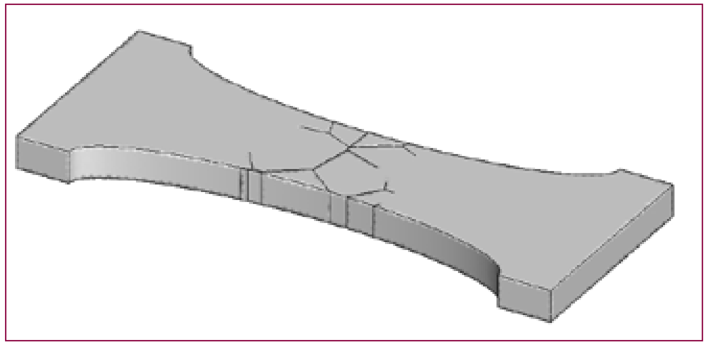
A natural way to numerically describe the mechanical problem is to reproduce the discrete crack propagation through a cohesive model in the framework of a finite element approach.

Because of the increasing complexity of the geometry and of the loadings involved in the microsystem industry, a three-dimensional description is often necessary; moreover, in order to obtain a good description of the mechanical behavior, in the vicinity of the crack-tip it is required a very fine mesh. All these assumptions lead to a computationally heavy numerical problem, whose solution becomes unfeasible.

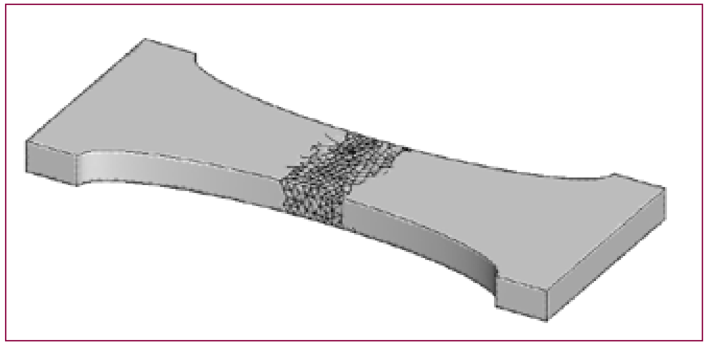
To handle with these issues, in the recent years domain decomposition techniques have been studied for elastic and, in some measure, also inelastic problems; in this work, an innovative domain decomposition, multi-time-step approach is developed, starting from the algorithm proposed by Gravouil and Combescure (2001), for the simulation of cohesive fracture problems in the context of polycrystalline silicon microsystems. The aims are: a) to exploit smaller fully elastic sub-problems whenever possible (i.e. in the regions far from where the crack is initiating or propagating), b) to overcome the time-step limits encountered with the standard description in an explicit dynamic scheme (i.e. the Courant condition), c) to take advantage of the parallel programming when dealing with large-scale problems.

A domain decomposition approach allows to efficiently handle the time integration and reduce the computational burden. Each sub-domain is modelled as linear elastic up to fracture and has an implicit integration scheme, then it switches to an explicit one, when a crack starts to propagates. Two time scales are then considered.

In fractured sub-domains, non linearity is assumed to concentrate along the fracture surfaces, while the bulk material remains linear elastic. This assumption holds, being the silicon brittle at room temperature. The crack propagation is described by a cohesive model, and is handled by an algorithm of automatic introduction of cohesive interface elements, whereas a critical stress level is exceeded.



2. Inter-granular crack propagation in a polysilicon dogbone specimen



3. Trans-granular crack propagation in a polysilicon dogbone specimen

As usual in a cohesive approach, fracture can develop only along the element faces. The constitutive behaviour of cohesive interface elements is described by a law linking the tractions acting at the crack surface to the displacement jump.

Fracture can propagate both inside subdomains and at the geometrical interface between them; both trans- and inter-granular propagation is considered.

The proposed numerical algorithm has been implemented in a three-dimensional finite element code. In particular, ten-node tetrahedra have been used for the bulk material meshes, while six-node triangles for the cohesive interfaces.

The proposed domain decomposition technique has been validated with reference to some fracture tests on isotropic materials. Simulations of fracture propagation in virtual polycrystalline solids, generated by a numerical procedure based on a three-dimensional Voronoi tessellation, have been performed.

A COROTATIONAL BEAM ELEMENT AND A REFINED MECHANICAL MODEL FOR THE NONLINEAR DYNAMIC ANALYSIS OF CABLES

Francesco Foti - Supervisors: **Luca Martinelli, Federico Perotti**

Introduction

Cables are very efficient structural members, widely used in several different engineering applications, among which we can cite: overhead electrical transmission lines, deployable structures, guyed masts and towers, tethered marine structures. Their slenderness and inherent flexibility implies that their dynamic response under many practical conditions can be strongly affected by various non-linearities, i.e. from geometrical effects, from the interaction with the environment, e.g. with fluid flows, and from the material constitutive law. This makes cable dynamics a complex and stimulating research topic, important both from a practical as well as from a theoretical point of view. As it can be inferred from a review of the recent literature, a very interesting issue, still open, is the development of reliable and efficient numerical procedures which can lead to a better and more accurate understanding of cables behavior, providing at the same time a valuable tool for design.
The objective of this research work is the development of a numerical procedure, suitable for large-scale structural analyses, to evaluate the mechanical response of metallic cables, accounting for their peculiar internal structure. In fact, as it will be further argued in the following, cables can be thought as made of non-isotropic composite materials. Several numerical models are currently available, based on a 3D finite element discretization of each individual component and an accurate description of the internal contact conditions, which play a key role both in local phenomena, e.g.: local stress determination, fretting fatigue and wear, and in some features of the structural response of such elements, e.g.: non-linear bending moment-curvature relations, structural-damping. These models, however, are computationally too expensive for large-scale structural analysis. This motivates our interest in searching for a link between classic structural theories and a refined description of ropes.
To this end, two main research lines were pursued, looking for innovative results in the field of modeling and simulation of the dynamic behavior of cables and, more in general, slender structural systems: (i) the development of a suitable cross-sectional constitutive law for metallic cables; (ii) the formulation of a new 3D slender beam element based on the principles of the well-known corotational approach.

Methodology

In this work, we propose a new mechanical model for metallic wire ropes, starting from an accurate description of their internal structure as an assembly of helical components in hierarchical levels, and in absence of a matrix. Each individual component of the rope is modeled by means of a well established structural theory for curved thin rods (Kirchoff-Love Theory). The interactions between components are considered by means of a contact model accounting also for internal sliding phenomena in presence of friction, which, as it is well documented in literature, can arise in presence of bending. The stick–slip conditions of each component are thus studied in the typical framework of incremental structural analyses, by defining a procedure based on an operator split into a frictional stick part and a frictional slip part and on a classical Return Map Algorithm. The response of the rope is then evaluated by summing all the contributions stemming from the individual wires. As an outcome, we obtain the desired constitutive law in terms of the cross sectional generalized stress and strains of the Euler-Bernoulli beam theory which can be exploited to describe cables as structural members reacting to a generic combination of axial force, torsion and biaxial bending. The proposed sectional constitutive law allows to describe some characteristic features of the mechanical response of wire ropes, such as the coupling between axial and torsional behavior and the hysteretic bending behavior. This kind of approach substantially departs from classical and well established structural theories for ropes, since it requires the development of an ad hoc slender beam element able to deal with large displacements and rotations, and with a non-holonomic material law.
This was the aim of the second research theme of this work, which finally led to the development of a new 3D corotational slender beam element. A crucial issue in the development of the beam formulation is the representation of 3D rotations, which, due to their non-commutative character, makes the configuration space of the structural theory non-linear. This aspect has been fully accounted for both in the formulation of the mechanical problem and in the numerical schemes adopted for its solution. The proposed formulation is based on the hypothesis of arbitrarily large nodal displacements and rotations, while strains are assumed small in a local (corotated) reference system which continuously rotates and translates with the element. Here a classic Euler-Bernoulli beam formulation is adopted. The internal forces and the element tangent stiffness matrix, together with a suitable symmetric approximation, are evaluated by systematically exploiting the principle of virtual work. The element formulation is developed regardless of the particular material behavior, so ensuring the compatibility of the structural element formulation with the non-linear cross-sectional behaviour of metallic wire ropes. In the proposed formulation a new procedure is also introduced for the evaluation of the inertia forces, which can be applied also to other corotational elements, in the general framework outlined in this work. Departing from the classical corotational approach, the kinetic energy of the element is here evaluated by employing only kinematic quantities defined with respect to the inertial frame of the structural problem. This avoids cumbersome calculations typically involved in corotational formulations and simplifies the treatment of the terms related to the 3D nodal rotations.
Finally, aerodynamic forces are accounted for by means of a superimposed 3D aerodynamic element, by slightly modifying a proven previous formulation.

Discussion

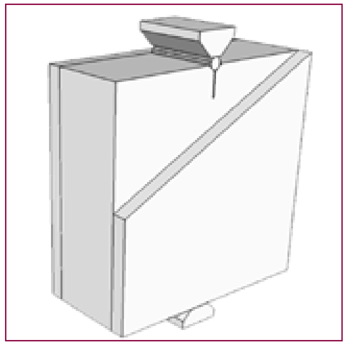
Numerical analyses were performed to validate the proposed formulations.
Classical benchmark examples demonstrated the good performances of the new finite element in evaluating the static as well as the dynamic response of beams undergoing large displacements and rotations. Subsequently, we proved the ability of the beam element, together with the new cross-sectional constitutive law, in reproducing the hysteretic character of the bending response of metallic wire ropes both quantitatively, with reference to established experimental results available in literature for a quasi-static bending test, as well qualitatively, by numerically simulating some classic decay tests on a short span line representative of typical laboratory conditions.
Finally, we illustrated the response of the beam element when applied in conjunction to the aerodynamic element.
To this end we considered a well documented cable in 1:2 "internal resonance" conditions, for which we studied both the static and dynamic response under a steady wind flow leading to the occurrence of self excited galloping vibrations.
The good results of the new beam element were here compared to those obtained by means of a well established cable finite element of literature and by a 3D corotational truss element developed as a minor contribution to this research work.

ADVANCED CEMENTITIOUS COMPOSITES FOR STRUCTURAL RETROFITTING

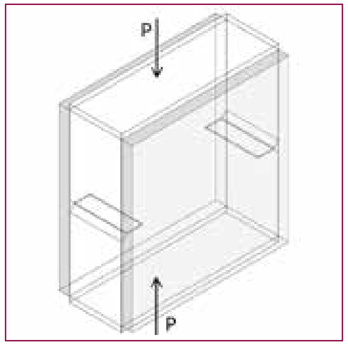
Anna Magri - Supervisor: **Marco di Prisco**

Strengthening of existing traditional concrete structures is becoming one of the most important issue for the structural engineering. This may derive from the necessity of retrofitting existing building to meet safety requirements in seismic zone where most buildings have been not designed to earthquake load or high wind pressure. The imminent need for upgrading existing structures has been taken into account by the development of different techniques including metallic grid reinforced surface coatings, shotcrete overlay, externally bonded Fiber Reinforced Polymers (FRP), Textile Reinforced Concrete (TRC), Ultra High Fiber Reinforced Concrete (HPFRC).
Traditional methods of seismic retrofitting fall for two main reasons: on one hand the request for an increase of strength and stiffness and on the other hand a mass reduction. The traditional solutions include the Reinforced Concrete (RC) jacketing or externally glued steel plates have some limits. In particular the use of RC jacket implies thickness greater than 60 or 70 mm that can increase too much the section and the mass of the element. The use of glued steel plates may have some problem in the case of fire resistance.
The purpose of this thesis is to illustrate the potential enhancement of structural safety limit state brought by the use of advanced cementitious composites. It is quite important to look for a retrofitting technique that can ensure the global structural safety of the building, the speed of the placing operations and the durability of the solution. The reduction of the time for the retrofitting operations is very important to reduce all the costs related to provisional housing and to the inactivity of the business activities. In this sense the use of TRC and UHPFRC can be a good way to achieve a strong and fast retrofitting solutions.
Textile Reinforced Concrete (TRC) is a good combination of high compressive and tensile strength that can lead to suitable load carrying capacity. This strengthening material allows the design of thin structure elements.
Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is characterized by a high tensile strength and ductility, reached by the slipping of steel fibres. The performance can be enhanced by orienting the flow during the casting procedure.
The research aims to study the effectiveness of strengthened layers (TRC or UHPFRC) on damaged concrete starting from the mechanical characterization of the materials.

A lot of time was spend to the design of TRC to find a proper combination between the fabric and the cement matrix. The parameters that influence the behaviour of the cementitious composite are multiple. The fabric can be varied for the geometry, the tensile strength, the warp and weft, the nature of the fibre and the way that they can be woven. The matrix must have a good workability to penetrate in the mesh of the fabric as well as the high tensile strength. The mechanical characterization of TRC was conducted by direct tensile test where specimens (40 x 70 x 6 mm) were reinforced with AR glass fabrics.
The strengthening materials were applied over a substrate layer made of traditional concrete that represents the structural element to be retrofitted. The effectiveness of the reinforcement were investigated referring both to uncracked and crack situations for the existing structure; in the case of cracked condition, SLS and ULS crack opening were considered. The improved performance of concrete occurs due to the transmission of tangential stresses through the contact surface which should be treated to increase bond mechanism. Usually in the real application a sandblasting treatment is used to make the surface rough where different pressure and size sand can be adopted.
A real innovation in this thesis was the technique adopted to investigate the effectiveness of the reinforcement layer, Double Edge Wedge Splitting (fig.1) that is an indirect tensile test that can be considered as an extension of Wedge Splitting (WS) because two are the wedge-shaped notches.
Up to now DEWS test has been used to identify the residual strength in the post-cracking regime of fiber reinforced concrete. Using this technique it was possible to combine several advantages. In principal the possibility of carrying out tensile tests by applying compressive loads, thus avoiding the typical problem of the direct tensile test on the specimen such as glued plates on the edges of the specimen to distribute the load. This aspect is common with other indirect tensile tests such as bending and Brazilian test, but with this technique, it is possible to minimize the structural effects. In particular the new test produces the stress distribution on the ligament of a notched specimen loaded in pure tension, without any crosswise compressive stresses. Furthermore DEWS test allows to compare the retrofitting specimen with the unstrengthened ones in terms of load capacity but above all in terms of ductility. This last performance is driven by the deformation of the strengthening material in the central length where delamination between retrofitting material and concrete occurred.



1. DEWS technique



2. Compression test

In addition to tensile tests, compression tests were performed. The specimens were rotated of 90 degrees respect to dews tests, in this way the pre-crack surface was perpendicular to the compressive load direction (fig.2). The loaded surfaces were not characterized by the notch and before the test were coated with a layer of mortar to make the surfaces smooth and plane thus avoiding possible localized failure where defects appear.
From a comprehensive experimental program some important conclusions can be highlighted.
By comparing the maximum load reached in the DEWS test by using TRC and UHPFRC layer in the three damage levels, TRC showed the best performances. Indeed the ratio between maximum load of the retrofitting solution and of the reference specimen is more than double. Furthermore the major ductility was reached in the TRC solution because the good bond at the interface surface allows to transfer the tensile stresses from the support to the strengthening layer. TRC multicracks in the central region where a portion of the layer is detached from the concrete plate.

AN EXPLICIT FINITE ELEMENT COMPUTATIONAL STRATEGY FOR THE SIMULATION OF BLADE CUTTING OF THIN SHELLS

Mara Pagani - Supervisors: **U. Perego**

The numerical simulation of cutting and fracture of shells and plates is a timely topic in computational engineering and is receiving increasing attention. Besides the rather obvious military applications, at the beginning of the 90's the mechanics of cutting a shell with a sharp object or tool has attracted particular attention in the field of naval engineering for the development of ship grounding models. An accurate numerical tool for the simulation of blade cutting would result extremely useful also in biomedical (especially surgical) applications. The development of a finite element model for the simulation of cutting of thin shells can be useful also for the simulation of the opening process of the thin membrane that seals a carton package.

The objective of the present work is to develop a finite element tool for the simulation of cutting processes implementing a computationally effective code based on a Fortran 90 Open MP architecture. The methodology has to take into account the high nonlinearities characterizing the problem, such as large strains, plasticity, fracture and contact. In these situations it is convenient to adopt an explicit dynamic approach which, despite its conditional stability, does not present the convergence problems which are likely to occur when using implicit solvers. Since the thin-walled structures involved in many engineering applications are typically layered composites undergoing both fracture and delamination during the cutting process, so-called solid-shell elements are used for the discretization rather than the more classical Mindlin-Reissner shell elements. Solid-shell elements have only translational degrees of freedom, present a simpler kinematics and allow for a complete 3D description of the material behavior resulting therefore more suitable for incorporating complex constitutive models and for simulating delamination processes.

The use of solid-shell elements in an explicit framework represents an interesting challenge. In fact, even if in the last decades a number of solid-shell elements has been proposed, in most cases they have been formulated in an implicit context. One of the main problems is connected with the fact that solid-shell elements are characterized by a dimension, the thickness, which is significantly smaller than the other two, leading to a high maximum eigenfrequency and, consequently, to a very small stable time-step, which is a not-negligible difficulty when explicit time integration is employed.

A selective mass scaling technique, based on a linear transformation of the element degrees of freedom, is here proposed to increase the critical time-step without affecting the dynamical response. An analytical procedure for the computation of the element highest eigenfrequency and for the estimate of the critical time-step size is also developed and an effective procedure for the selection of the optimal mass scaling factor is proposed.

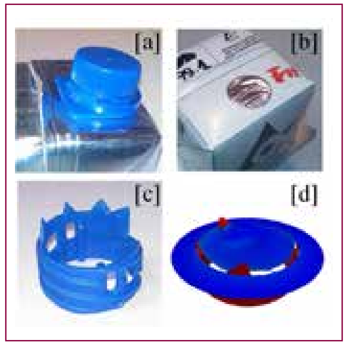
Despite some appealing features characterizing solid-shell elements, such as easy usage in combination with 3D solid elements and good accuracy in the through-the-thickness stress distribution, this kind of elements suffers several types of locking behavior. These faults can be controlled by means of the adoption of suitable techniques such as assumed natural strain (ANS) and/or enhanced assumed strain (EAS) corrections of the element kinematics. The computation of enhanced variables, requiring the solution of implicit nonlinear equations, can however be very expensive in terms of computational time when carried out in an explicit dynamics framework. In order to overcome this problem, an explicit estimate of enhanced variables is proposed. To guarantee a computationally efficient explicit architecture, an eight-node reduced integration solid-shell element is also implemented. It has one in-plane integration point and at least two integration points along the element thickness direction.

Reduced integration schemes suffer the development of hourglass spurious modes, which are controlled by the addition of hourglass stabilization terms that are discretely updated.

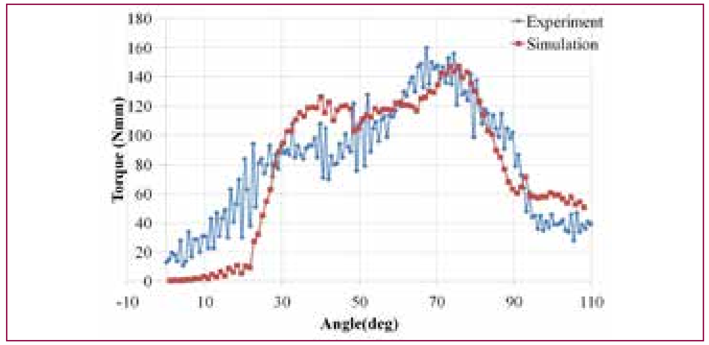
The simulation of cutting and fracture propagation is realized by means of a suitably developed cohesive approach. When the membrane material is very ductile or the blade cutter is sharp, classical interface cohesive elements, where the cohesive forces are transmitted in the direction of the crack opening displacement, cannot correctly reproduce situations in which the blade crosses the process zone. A simplified approach, based on the new concept of "directional" cohesive elements, is proposed to overcome this problem. These elements are geometric entities aimed at detecting contact with the blade within the fracture process zone and at transmitting cohesive forces to the crack flanks in directions which may be different from the direction of the straight line connecting facing points on the two crack sides.

TetraPak is a leading company in the carton-based food packaging market. The opening process of one of its carton packages provides an interesting example of application and validation of the proposed strategy. The objective of the opening process is to create a circular hole in a region of the package where a hole has been pre-laminated in the paperboard so as to reduce the force necessary to cut the laminate. In this way, in the hole region there is no paper and only thin aluminium and polymeric layers have to be cut. The hole has to be produced using an applied cap. Thanks to a screw thread, the cap rotation transmits the motion to the high-density polyethylene blades. The opening tool consists of several teeth which undergo a motion with both normal and tangential components to the laminate surface. Figure 1d shows the fracture pattern at the end of the numerical simulation. The comparison in terms of torque vs. rotation angle between numerical and experimental results is presented in Figure 2.

The proposed strategy, based on the implementation of solid-shell finite elements in an explicit context and the proposal of ad-hoc "directional" cohesive elements for the description of the fracture propagation, can be efficiently applied for the simulation of the cutting process of several types of thin structures. The introduction of a strategy for simulating the delamination process (not considered here) can further extend the scope of application of the proposed methodology and improve the accuracy of the simulation results.



1. Opening system: a) applied cap; b) package with pre-laminated hole; c) cutting teeth; d) fracture pattern at the end of numerical simulation

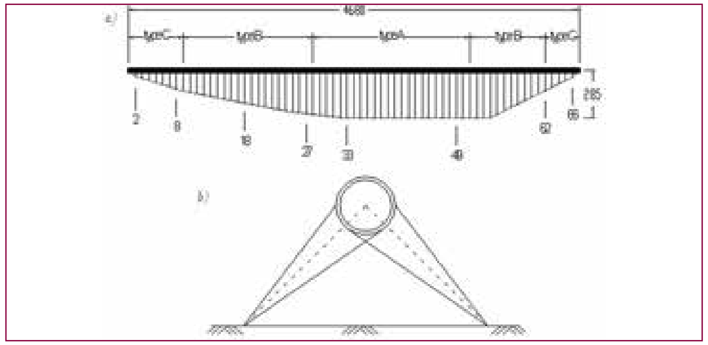


2. Torque-angle rotation graph. Experiment (diamond) vs numerical results (square)

PROBLEMS RELATED TO THE SEISMIC BEHAVIOUR OF SUBMERGED FLOATING TUNNELS

Chunxia Shi - Supervisor: **Federico Perotti**

SFT (Submerged Floating Tunnels), also known as Archimedes Bridges, are a new and innovative type of infrastructure. It serves as a revolutionary alternative to cross sea-straits, lakes and other waterways. Compared to suspended or cable stayed bridges, SFT can take advantage of the water buoyancy, this becoming a significant factor as length increases; when the comparison is made with underground or traditional immersed tunnels, the SFT has a clear advantage since it can be installed in very deep waters, where other crossing solutions cannot be applied.
The main aim of this work is to study the seismic behaviour of SFTs (including the seaquake effect). A prize-winning proposal for a SFT between Calabria and Sicily across the 350 m deep Messina strait in Italy is selected as an illustrative example of the simulation and analysis capabilities of the procedure developed. The model accounts for soil-structure interaction, geometrical and material non-linearities as well as for 3D multiple-support seismic excitation.
The length of the proposed SFT project across the Messina Strait is 4680 km, the maximum depth is 325 m, and the location of the floating tunnel is set 40 m under the water level. The following



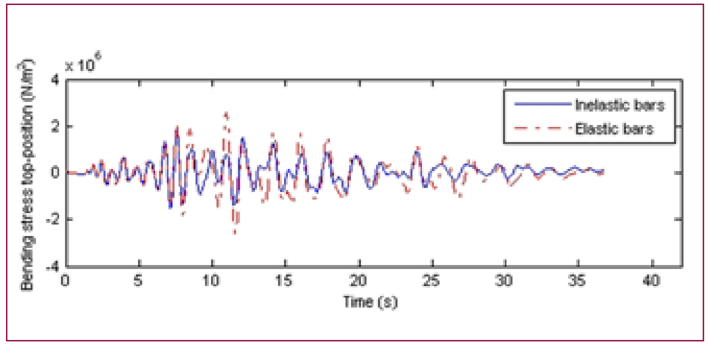
1. SFT, Front View (a), Section View (b)

Figure 1 shows the SFT's front and section views. The tunnel has a circular composite steel-concrete section; it is connected to the seabed by means of slender steel beams having hollow circular section and of pile foundations.

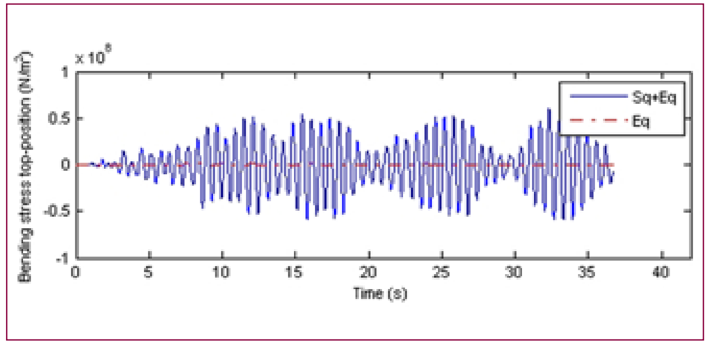
Non linear behaviour of the anchor bars and of the devices adopted for controlling the longitudinal motion, have a hack at decreasing the responses of SFT under generated artificial seismic excitation. In Figure 2, a comparison is given as an example to show the effect of the inelastic material, which reflects beneficial to reduce the bending stress of tunnel top-position at the mid-span in elastic and inelastic models.

Besides that, the seaquake effects are studied, working like an additional hydrodynamic loading arising from the earthquake transmission through water from the seabed. With the help of Morison equation, popular in calculation of the fluid force on submerged flexible circular columns, the seaquake pressure can be got knowing the seaquake velocity and acceleration which can be computed from the velocity potential.
A SFT 3-D inelastic model by accounting for seaquake excitation loading on the tunnel, in addition to the excitation previously considered. The seaquake effects can be seen from Figure 3. The 'Sq+Eq' represents the combination of seaquake and earthquake excitations while 'Eq' signals solely earthquake excitation. From Figure 3, the seaquake has a great effect on the structure responses, like bending stress of the tunnel top-position at the mid-span.

Both in elastic and inelastic models, a further investigation on the bars close to the shore should be carried out, given the extremely high demand in the quoted bars, probably exceeding the material capacity, and high internal forces in vicinal tunnel sections.
The work contributes to build up a solid background in the simulation of the structural response to seismic excitation including the seaquake, which is useful to many applications in offshore engineering. It also serves as the basis for the design of a first SFT.



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



3. Bending Stress of Tunnel Top-Position at the Mid-Span in Inelastic Model under 'Sq+Eq' and 'Eq' excitations

FREQUENCY AND TIME DOMAIN ANALYSIS ON FIBER REINFORCED POROVISCOELASTIC TISSUE: STUDY ON ARTICULAR CARTILAGE THROUGH NANOINDENTATION TESTS AT MICROMETRIC CHARACTERISTIC LENGTHS

Matteo Taffetani - Supervisors: **Pasquale Vena**

Articular cartilage (AC) is a paradigmatic tissue with respect to the concept of complex hierarchical tissue with structural function: it is inhomogeneous and anisotropic, it shows depth and time dependencies and it undergoes to large deformations. AC principal function of transferring loads between joints surfaces is performed by its specific microscopic structure: at these length scales, its characterization is still not well understood and recent works suggest interesting complexities that need deeper studies. This thesis is centered on the study of AC by making use of nanoindentation tests in both time and frequency domain, through experimental, numerical and analytical methods. The long term objective is focused on the developing of experimental and numerical methodologies for the early identification of AC pathologies.

The superficial layers of AC play an important role in both the biomechanics of the tissue and the maintenance of its integrity. Averaged properties can describe the overall mechanical behavior but they cannot catch the specific aspects of the local organization. Nanoindentation technique is well suited to this latter purpose, instead. The introduction of the concepts of characteristic lengths l_c, and equivalent deformations ε_{eq} allows to a better explanation of the results, giving the possibility to suggest relations between mechanical properties and specific microstructure: in case of spherical tip, $l_c = \sqrt[2]{Rh_s - h_s^2}$ and $\epsilon_{eq} = l_c/R$ where R is the indenter radius and h_s the indentation depth.

Two instruments are considered, an Atomic Force Microscope (AFM) and a Nanoindenter (NI): for the purpose of this thesis, they differ each other for the characteristic lengths and for the domain in which the experiments are carried out. The technique of dynamic mechanical analysis (DMA) is applied to a nanometric AFM–based nanoindentation whereas nanoindentation creep tests are used in conjuction with multiload tests at higher length scales. The dichotomy between poroelasticity (extrinsic phenomenon dependent on spatial derivative) and viscoelasticity (intrinsic phenomenon independent on spatial derivative) is investigated up to the role of the single bundle of fibers. The interest on high frequency behavior is related to the importance of instantaneous response (limit to the undrained condition) of the tissue. All the investigation are carried out on native AC.

Harmonic nanoindentation tests are performed using two spherical tips (radii $R_{7.5}$ = 7.5 μm and $R_{6.5}$ = 6.5 μm) and a conical one (C) at different indentation depths, up to a maximum of 2.3 μm with the larger one. The theory of Hertzian contact is used to compute both elastic and dissipative properties, through storage reduced modulus and tangent of the phase shift, respectively.

The elastic properties are depth-dependent for the whole frequency range: around 250 Hz (assumed as experimental undrained condition), a plateaux is reached. At 0 Hz (drained condition) the modulus shows a larger value with the larger spherical tip (hundreds of kPa) than with the smaller tips (tens of kPa). Dissipative effects decrease with the characteristic length: the tangent decreases from 0.7 to 0.3 for l_c increasing from 91 nm to 5.4 μm. A predominant poroelastic behavior is noted if the tissue is investigated with $R_{7.5}$ tip: the position of the peaks of the phase shift varies with the indentation depth. A mainly viscoelastic behavior, instead, characterizes the C tip. The correlations between the phenomena highlighted and the dimensions investigated are consistent with the superficial layers microstructural organization.

The NI is used in conjunction with the multiload creep test: recording creep data with different tips (radii R_{400} = 400 μm and R_{25} = 25 μm) at different load levels, while remaining in the same indentation spot, allows the investigation of the tissue at different characteristic lengths avoiding effects of tissue variability. At l_c from 15 μm to 125 μm, a predominant poroelastic behavior is evidenced and the poroelastic mechanical properties (drained modulus M_d, undrained modulus M_u and permeability k) are estimated by using the Hertzian theory and by adapting the analytical solution of the consolidation of a poroelastic layer subjected to a confined compression to this kind of test. For a constant load, the indentation depth in function of time is $h_s = h_{s,0} + P_1\, g(\tau)$ where $h_{s,0}$ is the instantaneous response, P_1 a parameter depending by the drained properties of the matrix and $g(\tau)$ a function dependent by $\tau = P_2/Rh_s = M_d k/Rh_s$, in case of spherical indentation. Experimental creep curves are fitted by the proposed equation to find optima parameters P_1 and P_2. Values of drained modulus found with R_{25} tip are higher than those found with the larger one (1.7 MPa vs 0.5 MPa), suggesting a dependence with the equivalent strain. k is estimated locally and it is found decreasing with the strain applied.

Proper numerical methods can help the explanation of experimental evidences by highlighting the effect of hidden (from an experimental point of view) parameters on the overall response.

The problem of DMA test of spherical nanoindentation on poroelastic material is implemented in an homemade Matlab (MathWorks, Natick, MA, USA) based code. The effect of geometrical and constitutive parameters are studied. Radii ([400; 125; 25; 75] μm) and indentation depths ([40; 12.5; 2.5; 0.75] μm) are varied while an isotropic poroelastic material is considered: indentation radius has a larger effect on the real part of the material response than indentation depth. Anisotropy ratio, ratio between the transversal and the axial stiffness, and out-of-plane Poisson's ratio of a transversely isotropic poroelastic material, instead, are varied maintaining a thermodynamic consistency: while the geometry is kept fixed (radius 7.5 μm and indentation depth 0.75 μm), it is shown that the weight of dissipative effect increase when an highly anisotropic material is considered. The model is also used in a parameter identification process based on the frequency domain experimental results obtained with the larger spherical tips and suitably constitutive parameters of a transversely isotropic poroelastic material are identified: an anisotropy ratio around 0.15 is found constant throughout the indentation depths investigated ([0.5 – 2.3] μm).

The physical complexity of AC requires numerical models capable to take into account for all the single components and their mutual interactions, especially if a micrometrical characterization is the objective. One recent approach, indeed, is related to the direct modeling of tissues constituents and their interactions. In this thesis, a poroviscoelastic constitutive relation with a continuous fiber distribution is implemented in a user defined material subroutine for the commercial code Abaqus 6.8-EF1 (Simulia, Providence, RI, USA): the role of solid matrix, proteoglycans and collagen fibers are accounted for. The fiber distribution is modeled as a three parameters ellipsoid in an axisymmetric framework. A sensitivity analysis is performed on those parameters by using a confined compression stress relaxation tests. Only a preliminary attempt to apply this model to the collected experimental data is proposed: indeed, this material is used to obtain the input configuration for the dynamic code and it is shown that, for a fixed set of constitutive parameters (related to constituents), a unique fibers distribution permits to replicate the results obtained varying the indentation depth of 1 μm, from 0.5 to 1.5 μm from the surface.

Finally, the protocol developed in time domain is used to evaluate the mechanical properties of engineered AC, when it is subjected to different treatments after injury: the estimated poroelastic parameters shown differences that can be positively correlated with the different microstructural arrangements. Therefore, this methodology appears a promising tool to be used for clinical applications.