MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | SPATIAL PLANNING AND URBAN DEVELOPMENT | **STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING** | TECHNOLOGY AND DESIGN FOR ENVIRONMENT AND BUILDING | TERRITORIAL DESIGN AND GOVERNMENT | AEROSPACE ENGINEERING | ARCHITECTURAL AND URBAN DESIGN | ARCHITECTURAL COMPOSITION | ARCHITECTURE, URBAN DESIGN, CONSERVATION OF HOUSING AND LANDSCAPE | BIOENGINEERING | BUILDING ENGINEERING | DESIGN | DESIGN AND TECHNOLOGIES FOR CULTURAL HERITAGE | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | INTERIOR ARCHITECTURE AND EXHIBITION DESIGN | MANAGEMENT, ECONOMICS AND INDUSTRIAL ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2016

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
Prof. Roberto Paolucci

Objectives of the Doctoral Program

Structural, Seismic and Geotechnical Engineering - SSGE encompasses 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 formicro-systems), (b) structural systems (from constructions to bio-mechanical systems and micro-systems), (c) soils, and (d) environment-structure 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 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 at Politecnico di Milano or at 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 many 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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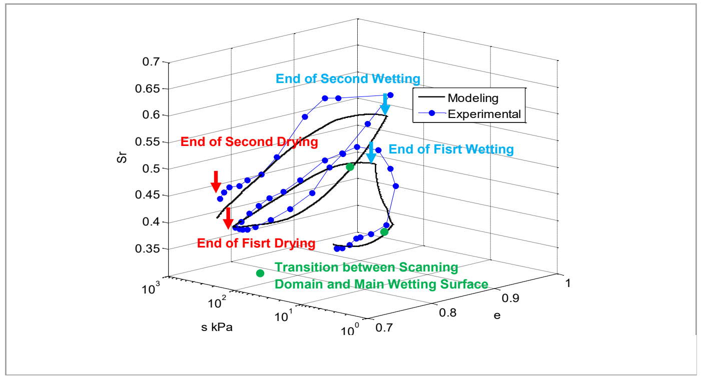
EFFECTS OF REPEATED HYDRAULIC LOADS ON THE HYDROMECHANICAL RESPONSE OF AN UNSATURATED SILTY SOIL

Arash Azizi

Supervisors: Prof. Cristina Jommi, Prof. Guido Musso, Prof. Gabriele Della Vecchia

Soils used in earth constructions are mostly unsaturated, and they undergo frequent wetting-drying cycles due to changes in the climatic conditions, particularly at shallow depths. Repeated hydraulic loads are also induced in levees and dykes by changes in the water height, which affect the extent of the unsaturated zone. Changes in water content significantly influence the hydromechanical behaviour of the construction material, which therefore has to be assessed for repeated hydraulic loads. This research work investigated the coupled hydromechanical behaviour of a silt, typically used in the construction of dykes, with the aim of providing a better understanding of the consequences of wetting-drying cycles in the field on the overall response of the material.

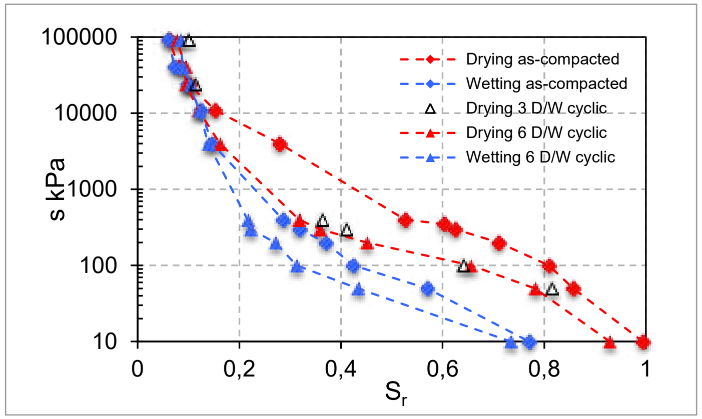
The soil was studied in the laboratory by means of a comprehensive series of complementary experimental tests. The first series involved wetting-drying and loading-unloading stress paths applied in suction-controlled oedometer. Irreversible changes in the degree of saturation implied that hysteresis of water retention is induced by changes in the suction and volume of soil samples. A rate form of the water retention curve (WRC) model was proposed to simulate the hysteresis, in which the contact angle was used to express the dependence of the response on non-monotonic changes in suction and void ratio. A constitutive hypo-plastic model was then proposed and coupled with the contact angle-WRC model to account for the coupling between the hydraulic and the mechanical behaviours. The model was then employed to simulate the experimental hydromechanical response observed in laboratory tests (Figure 1).



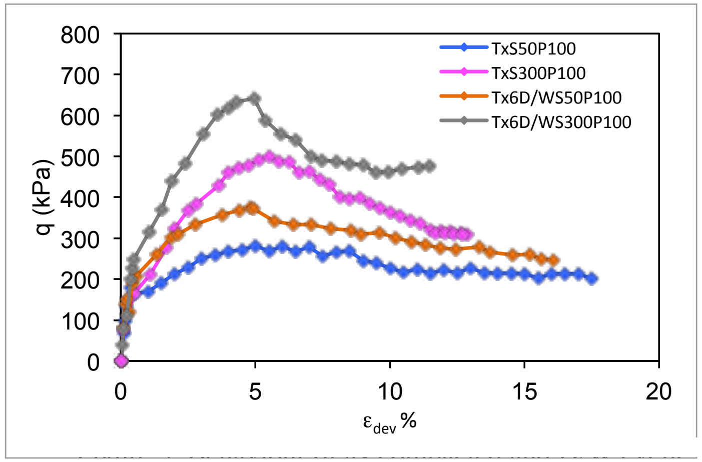
1. Comparing experimental behaviour and modelling prediction during drying–wetting cycles at constant axial net stress in S_r–s-e space

The second series of experimental tests was performed to study the impact of wetting-drying cycles on microstructural features and hydraulic properties of as-compacted samples. When as-compacted samples were subjected to wetting-drying cycles, fabric changes took place due to interactions between different structural levels even though no significant total volumetric strain occurred. The hydraulic repeated loads changed the soil fabric by forming larger pores, resulting in fundamental changes in their hydromechanical response. As shown in Figure 2, samples subjected to 3 and 6 cycles of drying-wetting (named as 3 and 6 D/W cyclic samples, respectively) exhibited mainly the same water retention behaviour but different from the as-compacted one. The new WRC model was proposed accounting for different structure levels and an evolving pore size distribution of the tested materials.

Eventually, the effects of repeated hydraulic loads on the mechanical behaviour of the silt were studied using constant water content triaxial tests. The hydraulic repeated loads changed the soil fabric by forming larger pores, resulting in fundamental changes in their hydromechanical response. The hydraulic repeated loads increased the compressibility of the soil at low-stress levels. Since samples subjected to repeated hydraulic loads experienced more volumetric contraction during compression, they became slightly denser than the as-compacted one being subjected to the same stress level. Moreover, when such samples subjected to the same suction, their hydraulic state changed with respect to their corresponding water retention curves, where samples subjected to repeated hydraulic loads expelled more water than the as-compacted one, and hence, such samples became stiffer and exhibited higher strength associated with dilative behaviour during subsequent shear loading. As shown in Figure 3, samples subjected to repeated hydraulic loads (Tx6D/WS50P100, Tx6D/WS300P100) showed higher deviatoric stress and more evident post-peak softening comparing to as-compacted samples (TxS50P100, TxS300P100) when subjected to the same suction and mean net stress.



2. Effect of repeated hydraulic loads on the water retention behaviour in S_r-log(s) plane



3. Behaviour of as-compacted and D/W cyclic samples during the shearing phase in q- ε_{dev} plane (s=50 and 300 kPa, P_{net}=100 kPa)

MECHANICAL CHARACTERISATION AND BOND BEHAVIOUR OF FIBRE REINFORCED CEMENTITIOUS MATRIX MATERIALS FOR STRENGTHENING OF MASONRY STRUCTURES

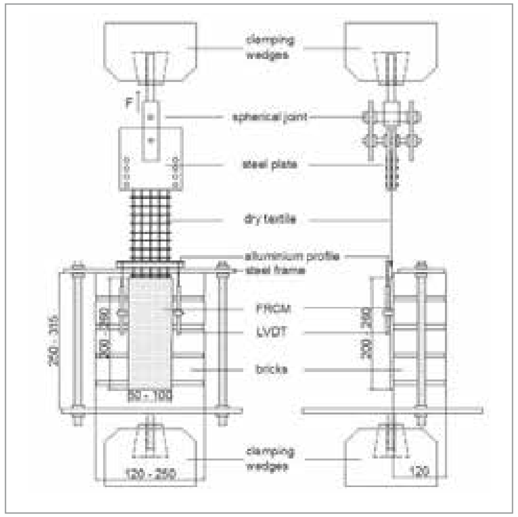
Giulia Carozzi - Supervisor: Prof. Carlo Poggi

Co-Supervisor: Prof. Pierluigi Colombi

Continuous fibres reinforced materials are widely used for strengthening and anti-seismic retrofitting of existing masonry structures. Among non conventional reinforcing systems, the most popular one is composed of fibres textile impregnated with an epoxy resin (FRP). The system is characterized by high mechanical properties, lightness and speed of execution, but the compatibility with the masonry substrate is poor, and it presents also poor behaviour at high temperatures. In order to solve these problems, the fabric reinforced cementitious materials (FRCM) were recently proposed in practical applications. These materials are composed of a dry fibres grid embedded in an inorganic matrix eventually enriched with short fibres. FRCMs are particularly indicated in the reinforcement of historical buildings due to the high compatibility with the substrates, better reversibility, vapour permeability and durability to external agents.
The main objective of this thesis is the investigation of the mechanical properties and bond behaviour of Fabric Reinforced Cementitious Matrix materials.
Very limited works are available in literature about the investigation of the mechanical behaviour of FRCM systems. This thesis represents a contribution for the knowledge of these aspects and provides data and critical considerations for the development of guidelines and design recommendations for the use of FRCM systems in the practical applications.
The work is divided in three parts. In the first part, the mechanical behaviour of the system in tension is analysed. Preliminary tests (Fig. 1) are performed to know the mechanical properties of the components, and then a series of tensile tests is carried out. FRCM systems with different constituent materials and geometries were analysed. In particular, the influence of the test set-ups and instrumentation, and the evaluation of the main mechanical parameters are described.

1. Tensile tests on dry yarn and FRCM system

In the second part, the bond behaviour of the system applied on a masonry substrate is investigated. The analysis of the failure modes and the bond properties are very important to understand the behaviour of the materials and the more important parameters required for design. A large experimental campaign was performed on different FRCM materials applied on masonry substrate. In particular, systems composed of glass, carbon and PBO textile with different geometries and bonded with cementitious or lime based mortar are considered. Both single (Fig. 2) and double lap set-ups are considered. The influence of the mechanical and physical materials properties and geometries is analysed. The failure modes could significantly change between the different systems. The more common one is the textile slippage within the mortar matrix. In some cases also the cracking of the mortar or the splitting of the first mortar layer, or the tensile failure of the fibres could be observed.
An analytical formulation of the bond strenght behaviour of the system is proposed and validated through the experimental results. Initially, the analytical bond strength models available in literature with reference to both the FRP and FRCM materials are critically reviewed. Furthermore, a bond strength model is proposed to analyse the bond between FRCM materials and masonry.
A trilinear shear stress-slip relationship is adopted; where the last phase of the bond-slip model is characterized by a constant shear stress in order to model the friction phenomena between the matrix and the fabric
In the third part the out-of-plane behaviour of a masonry panel reinforced with FRCM systems was experimentally investigated. A series of three points bending tests was performed on masonry elements reinforced with two different FRCM materials. Both solid and hollow clay bricks were used in order to simulate the behaviour of structural elements and infill walls subjected to an horizontal load perpendicular to the horizontal mortar joints. The study of the out-of-plane phenomena developed in the light walls during a seismic event is very important because these non-structural elements are very common in modern building and often subjected to many damages under horizontal loads. The typical failure mode (Fig. 3) shows initially the cracks of the inorganic matrix and of the substrate. Then the slippage of the textile respect to the mortar is achieved with increasing of the load.
At the end of this thesis, critical considerations on the experimental and analytical results are presented in view of the preparation of guidelines and design recommendations for the use of these reinforcement systems in the rehabilitation of masonry structures.



2. Shear test set-up

3. Bending test: failure mode

MECHANICAL EFFECTS OF SULFATE ATTACK ON CONCRETE: EXPERIMENTAL CHARACTERIZATION AND MODELING

Nicola Cefis - Supervisor: Prof. Claudia Comi

When a concrete structure is located in environments naturally rich in sulfates a series of deleterious reactions can occur inside the material. During the process called sulfate attack the anions of sulfate, coming from the external environment or released by the cement paste in the presence of water can diffuse and react with the constituents of cement (gel *C-S-H* and calcium hydroxide) forming gypsum which in turn reacts with the hydrate calcium aluminates present in the cement paste. The final product of these reactions is the secondary ettringite, an expansive phase that, forming within the hardened matrix, can generate states of stress inside the material. The mechanical effects of these chemical reactions consist in a progressive decrease of the stiffness and strength of the material. This is due to two different phenomena: a chemical damage due to the leaching of silicate hydrates and calcium hydroxide and a stress-induced mechanical damage due to the expansion of ettringite in the pores. The macroscopic consequences on structural elements can be very serious, up to compromise the reliability and the safety of the entire construction. The performance of a structure subject to sulfate attack depends on a large number of strongly interacting factors both of physical-chemical nature (molar concentrations, diffusivity and reactivity) and of mechanical nature (material strength, fracture energy, ...) therefore it is very difficult to predict the real structural behavior. The objective of this thesis is the study, both from the experimental and theoretical point of view, of the mechanical effect of sulfate attack in concrete.

A first objective of this work is to obtain an adequate experimental database on concrete, under different exposure and confinement conditions. To this purpose, an experimental campaign on concrete specimens, produced with two different cements has been launched and is still ongoing. During the experimental campaign samples of concrete were placed in different exposure conditions to produce sulfate attack. Periodically weight variations and macroscopic deformations were measured and the damage of the material was indirectly measured through ultrasonic wave propagation measurements. After 400 days of immersion a series of chemical and physical characterization tests were conducted: X-ray Diffraction, Scanning Electron Microscope observations and Energy Dispersive X-ray Spectrometry.

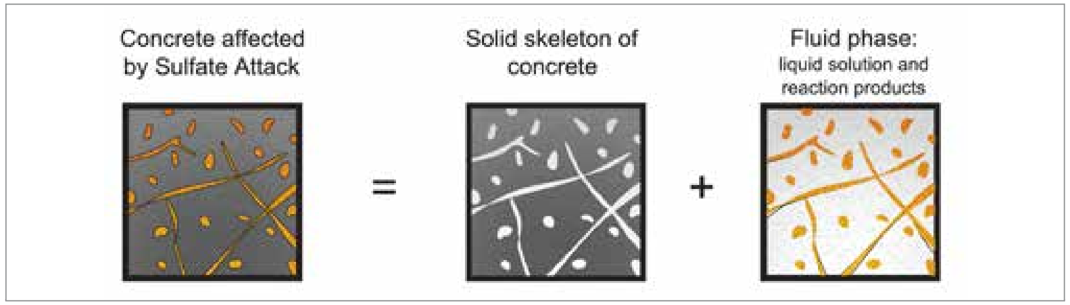
1. Macrocraking in concrete specimen due to the formation of secondary ettringite

The second objective of the thesis is the development of a model and of a numerical strategy for the chemo mechanical analysis of concrete affected by the sulfate attack. Within the framework of the Biot's theory, the concrete subject to sulfate attack is represented by the superposition of two phases: the homogenized concrete skeleton and the homogenized fluid which includes the pore solution and the expansive reaction products.

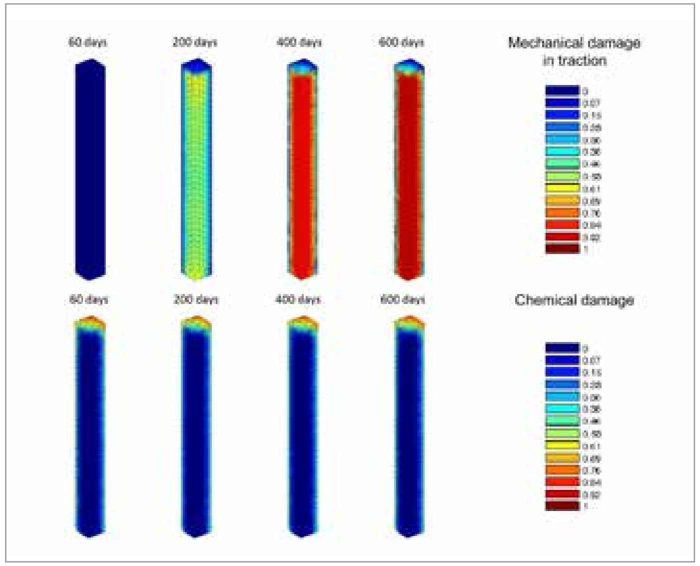
Initially the pores are totally saturated with water but, due to the reaction, acicular crystals of ettringite gradually grow and exert a isotropic pressure on the solid matrix. The evolution of chemical species during the reaction is computed by a proper chemical model in which the diffusion process of the sulfate in the material and the reaction with the aluminates naturally present in the cement paste are simulated in a coupled form. The amount of ettringite produced is directly related to the difference between the initial and actual amount of calcium aluminates. During the chemical process a part of the solid is consumed due to the leaching and the expansive ettringite can develop in the total porosity given by the sum of the porosity naturally present in concrete and the additional porosity due the leaching process. The state laws of the constitutive model are derived from the free energy, which depends on strains, variation of fluid content and internal variables. In particular an internal variable of chemical damage and two internal variables of mechanical damage (for prevailing state of tension and compression) are introduced.

Starting from this model, valid in the case of fully saturated conditions, an extension to partially saturated condition is proposed. In the case of weakly permeable materials, like concrete, the description of the transport of moisture is carried out through a simplified model in which the only variable is the degree of saturation. The unsaturated conditions modify the kinetic of the diffusion of sulfates within the homogenized material: the model has been suitably modified to take into account the effect of the gradient of the water content on the diffusion of ions.

The proposed model and approach are calibrated and validated by comparison of the obtained numerical predictions with experimental on mortar and concrete both taken from the literature and obtained in our experimental campaign. The model showed a good capability to simulate the most important aspects of the phenomenon in different conditions. A good agreement is obtained between the experimental data and the numerical results in terms of macroscopic deformation, mass variation and depth of penetration of the salts. Furthermore, the internal pressure computed with the developed model is in reasonable agreement with that obtained through the crystallization theory.



2. Bi-phase model: concrete in a superimposition of two phase (solid skeleton and fluid phase)



3. Mechanical and chemical damage in mortar prism subject to external sulfate attack at different time.

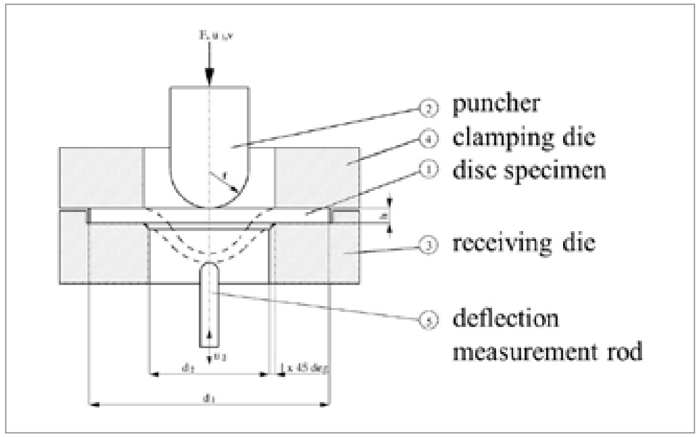
IDENTIFICATION OF BOTH MATERIAL PARAMETERS AND RESIDUAL STRESSES BY QUASI-NON-DESTRUCTIVE TESTS AND INVERSE ANALYSES

Aram Cornaggia - Supervisor: Prof. Giuseppe Cocchetti

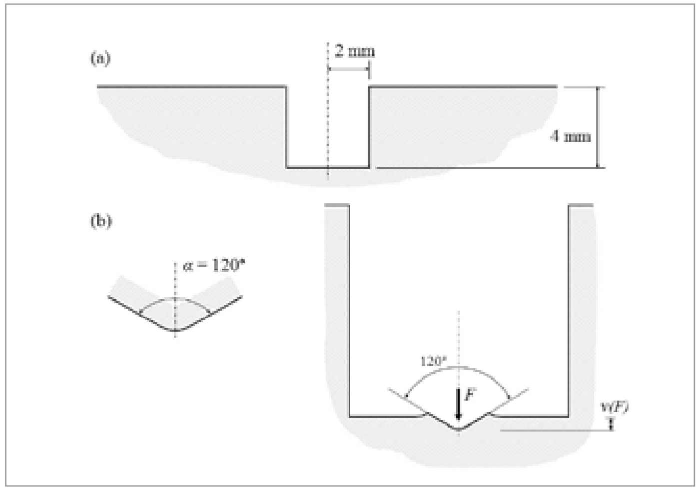
Co-Supervisor: Prof. Giulio Maier

In present engineering practice, structural diagnosis is a subject of growing interest, particularly for computations of safety margins or residual service life of monitored structural components and structures. In the present thesis diagnostic aims are devoted to identification of both material parameters and residual stresses, with reference mainly to metallic structural components. The mechanical characterization of materials (namely, the identification of parameters in preselected constitutive models) can be considered of interest in practical applications especially for structural components in which the original mechanical properties might be deteriorated in time. As an additional kind of information for structural diagnosis, the possible presence of residual stresses (namely, self-equilibrated, frequently superficial, distribution of stresses) should be investigated, since their effects could significantly reduce the safety margins for the analysed structural components.
Among the diverse experimental methods nowadays available, in the present study "quasi-non-destructive" tests are adopted. Specifically, the presented methodologies and research results deal with: Small Punch test (SP) and relevant sample extraction (preSP); Hole Drilling (HD) combined with instrumented Indentation (IND). Both these research issues are intended to provide a complete methodology for the identification of material parameters and residual stresses. The choice of "quasi-non-destructive" tests, instead of traditional "destructive" tests on specimen extracted and brought to a laboratory, is strongly motivated by reduced damages, times and costs and by, possibly, execution in situ (sometimes even without interruption of in-service working of structural components). The advantages in comparison with "non-destructive" tests (e.g. by diffraction method or ultrasonic emission) rests on possibility of inelasticity characterization and frequently on more accuracy of parameters estimations.
From a computational point of view, as now spreading in structural diagnosis, inverse analysis (or back-analysis) procedures are considered herein as methodology for parameter identifications. With respect to traditional empirical approaches, back-analyses are based on mechanical and mathematical tools, namely mechanical simulations of the tests and identification of parameters through numerical minimization of a suitably formulated difference between experimental data and their counterparts computed as functions of the searched parameters. Such methods provide, in general, more accurate and reliable results for parameters identifications than the traditional practice.
A further step on the estimation of material parameters and residual stresses can be achieved by the adoption of stochastic approaches for inverse analyses. In particular, in this work, Kalman filters are selected, among the diverse methods available in literature, for the estimations of parameters and their uncertainties, with practical advantages for the reliability of the results and for the diagnostic aims.
As for areas of practical applications of the proposed methodologies, examples can be found in diverse engineering contexts, e.g. civil, mechanical, aeronautical, particularly on structural components in hydro- or thermo-electrical power plants or offshore platforms.
The aims and results of the present thesis can be outlined as follows.

a) The adoption of inverse analysis approaches for identification procedures based on already known experimental techniques for material parameters estimation and for residual stresses assessments, in order to provide in a more fast and economical way more reliable estimates to diagnostic purposes, with respect to the present praxis and standards.
b) The innovative combination of two already available experimental techniques for the development of methods for identification of both material parameters and residual stresses. Namely: combination between Small Punch testing for material characterization and the relevant sample extraction exploited for residual stresses estimation; as a novel method alternative to the preceding one, the combination of Hole Drilling, intended for assessment of stress parameters, with instrumented Indentation for mechanical characterization of materials.
c) The development of stochastic back-analyses, here by Kalman filters, for estimation of the unknown parameters (both material constitutive properties and stress states) and for the assessment of their randomness due to experimental "noises" and to other uncertainties, in order to provide more meaningful results as for diagnostic aims concerning possibly damaged structural components.



1. Sketch of a typical Small Punch system (CEN CWA 15627).



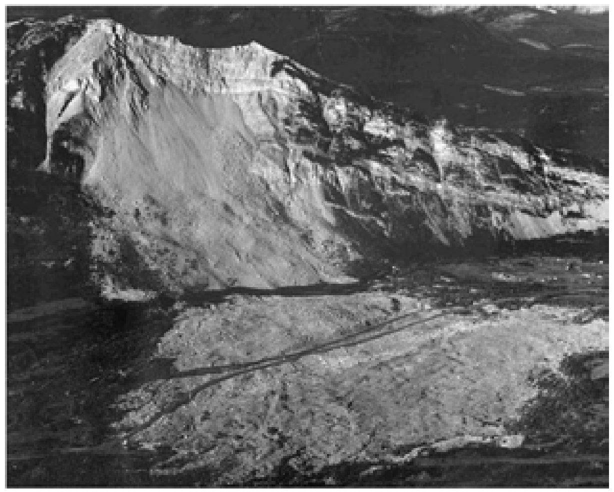
2. Cylindrical shape of the hole generated by standardized Hole Drilling tests (a); Indentation after a HD test (b).

THREE-DIMENSIONAL NUMERICAL SIMULATION OF LARGE SCALE LANDSLIDES

Francesco Ferri - Supervisor: Prof. Umberto Perego

The assessment of landslide hazard has become a topic of major interest not only for geoscientists and engineers but also for the community and the local administrations, in Italy and in many parts of the world. The reason for international interest in landslides is the increasing awareness of the socio-economic impact of landslides and the increased presence of development and urbanization on the environment, often in mountainous terrains. Flow-like landslides, for example debris flows or rock avalanches, due to high velocity and in some cases due to not preventable triggering mechanism (e.g. earthquake) are among the most dangerous events.

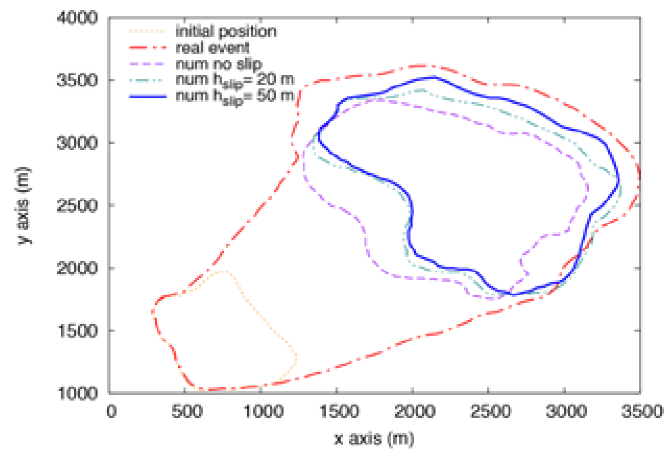
Modelling such kind of landslides is important for the creation of accurate maps of hazardous areas, to estimate the entity of the hazard and finally to design appropriate protective measures. Starting from a two dimensional numerical tool for fluid-structure interaction problems, implemented by Cremonesi, a three dimensional Lagrangian numerical approach, for the simulation of rapid landslides, has been developed. The simulation approach is based on the so called Particle Finite Element Method (PFEM), first proposed by Oñate, Idelsohn and coworkes. The moving soil mass is assumed to obey a rigid-viscoplastic, non-dilatant Drucker-Prager constitutive law, which is cast in the form of a regularized, pressure sensitive Bingham model.
Unlike in classical formulations of computational fluid mechanics, where no-slip boundary conditions are assumed, basal slip boundary conditions are introduced to account for the specific nature of the landslide-basal surface interface. The basal slip conditions are formulated in the form of modified Navier boundary conditions, with a pressure sensitive threshold. The proposed interface law is characterized by two parameters: the slip height and the basal friction angle.
A special mixed Eulerian-Lagrangian formulation is used for the elements on the basal interface to accommodate the new slip conditions into the PFEM framework. To avoid inconsistencies in the presence of complex shapes of the basal surface, the no-flux condition through the basal surface is relaxed using a penalty approach.



1. Frank rock avalanche. View of the final deposit

The proposed model is validated by simulating both laboratory tests and large scale problems. In particular, the well-studied cases of the Frank avalanche (figures 1 and 2) and the Vajont slide are presented. In the latter the mobilized material slips into the water reservoir, generating a huge wave. In this case, both the terrain and the water have been modelled and simulated.

Another subject considered in this work, is the implementation of a nodal integrated formulation instead of the standard elemental integrated formulation. An advantage of the Lagrangian approach for the fluid flow is that the convective terms in the momentum conservation disappear, and the difficulty is transmitted to the necessity to frequently retriangulate the mesh.
When retriangulation is performed, data have to be transferred from the old mesh to the new one. In this approach, to avoid interpolation from mesh to mesh, only degrees of freedom of particles located at the vertices of triangles, in 2D, and tetrahedra, in 3D, are used, so that only linear shape functions can be used for both velocity and pressure. Nevertheless, some quantities like strains, stresses and densities have to be evaluated in the elements to perform the integration. This can lead to some problems if more than one material is considered (e.g. terrain and water). A remedy to avoid this obstacle, and in view of a future parallel implementation of the code, a 2D approach based on nodal integration has been developed.



2. Frank rock avalanche. Landslide track and final deposit. Comparison between experimental observation and simulation with different slip lengths.

VIBRATION-BASED STRUCTURAL HEALTH MONITORING FOR HISTORIC MASONRY TOWERS

Marco Guidobaldi - Supervisor: Prof. Carmelo Gentile

Structural Health Monitoring (SHM) has significantly grown in importance in civil engineering applications, due to the increasing need of controlling a large number of ageing and complex structures. SHM based on Operational Modal Analysis (OMA) represents a sub-group of the SHM methodologies that is based on the identification of the modal parameters of a structure (i.e. frequencies, damping ratios and mode shapes) subjected to ambient vibrations. Indeed, one of the main advantages of OMA-based SHM is the possibility of assessing the structural health condition under operational loads and with no need for artificial inputs. Because of its non-destructive and sustainable way of testing, OMA-based SHM represents an investigation technique particularly suitable to Cultural Heritage.

Within the framework of Cultural Heritage, ancient masonry towers represent a very common typology of structure characterized by different functions and features: bell towers, lookout or defensive towers, chimneys, minarets, etc. Other than the common issues of historic buildings (i.e. ageing of materials, presence of cracks and damage, effects of successive construction phases or modifications), historic masonry towers are usually also particularly vulnerable to dynamic actions (e.g. swinging of bells, wind and earthquakes, etc.) due to the slenderness of their geometry and to the presence of significant dead loads. This makes preservation and preventive conservation of historic towers a major challenge in the SHM of Cultural Heritage. Nevertheless, as historic towers are usually sensitive also to ambient excitation , ambient vibration tests (AVT) are more frequently adopted to assess the current global behavior of the structure. Furthermore, the cantilever-like structural scheme of towers allows an effective dynamic monitoring with just few accelerometers installed in the upper part of the building, resulting in a sustainable system that can be successfully used for preventive conservation and/or SHM purposes.

In the Doctoral Dissertation, a specific vibration-based strategy of SHM has been proposed for historic towers. The proposed approach is based on the availability of appropriate knowledge of the structure obtained through traditional data collection (i.e. historic and documentary research, on-site and topographic survey, visual inspection, non-destructive and minor-destructive tests of materials on site) and consists of the following tasks:

a) preliminary AVTs: the number of sensors (i.e. accelerometers and temperature sensors) and the duration of the tests have to be properly selected in order to provide useful indications for the subsequent long-term monitoring (i.e. accurate estimates of the dynamic characteristics, positions to be permanently instrumented, influence of the environmental factors);
b) installation of a continuous dynamic monitoring system as simple as possible (i.e., consisting of 3 accelerometers and few environmental sensors) and use of state-of-art tools for automated modal identification: in particular, an automated procedure based on the SSI-Cov technique has been applied to continuously identify the modal parameters from the recorded responses;
c) preliminary analysis of the time evolution of natural frequencies, used as damage-sensitive features, in order to highlight the correlation with changing environmental factors, such as temperature;
d) removal (minimization) of the environmental effects on the natural frequencies: once the impact of changing environment on natural frequencies has been recognized, Dynamic Regression models, ARX models and Principal Component Analysis (PCA)-based tools can be applied to remove/minimize the influence of extra-structural factors on the natural frequencies. The cleaned natural frequencies and/or the residual errors, in principle, only depend on the structural condition and can be adopted as damage-sensitive features;
e) detection of abnormal structural change and damage: the residual errors have been used to check the occurrence of abnormal structural changes, directly or by means of the statistical tool referred to as *Shewhart T* control chart. Control charts are essentially plots where the evolution in time of a certain feature is represented along with user-defined variation limits. The control limits are computed from the experimental samples collected during an appropriate reference period. This allows to associate any observation laying outside of the defined limits to the presence of unusual sources of variability (e.g. the occurrence of damage).

The outlined methodology has been firstly exemplified on data collected for about 30 months on the *Gabbia* tower (XIII century, 54.0 m high) in Mantua, Italy. After the Italian seismic sequence of May 2012, Politecnico di Milano (Polo Territoriale di Mantova) was committed to assess the structural condition of the structure. Subsequently, a continuous dynamic monitoring system (including 3 highly sensitive accelerometers and 1 temperature sensor) was installed in the tower with the main objectives of (a) evaluating the effects of temperature on the natural frequencies of the building; (b) evaluating the dynamic response of the tower to the expected sequence of far-field earthquakes; (c) detecting any possible anomaly or abnormal change in the structural behavior.

The use of 1 temperature sensor allowed successfully estimating the effects of temperature, which have been subsequently minimized/removed by means of linear Dynamic Regression, ARX and PCA models.

About six months after the beginning of the continuous monitoring, the tower was hit by a far-field earthquake and the maximum measured acceleration exceeded by about 40-50 times the highest level of normally observed ambient vibrations. The inspection of frequency tracking, the correlation between modal frequencies and temperature, the residual errors estimated from Dynamic Regression models and the related control charts clearly indicate the occurrence of abnormal and permanent structural changes induced by the earthquake. The same conclusion was drawn from the control charts based on ARX models and PCA tools. Those results provide a clear evidence of the possible key role of continuous dynamic monitoring and of the adopted methodology in the preventive conservation of historic towers.

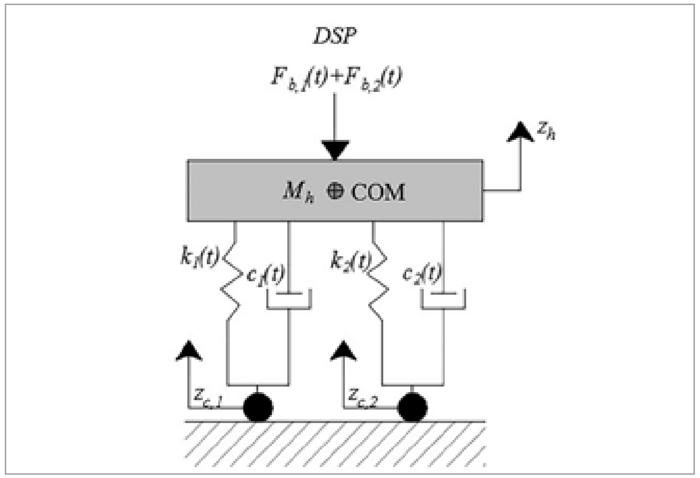
To further investigate some tasks of the adopted SHM methodology, the bell tower of the *Chiesa Collegiata di San Vittore* in Arcisate has been examined. The structure is about 37.0 m high and built in irregular stonework masonry. A continuous dynamic monitoring program (again using 3 accelerometers) was performed on the tower from June 2009 until February 2010. In this case temperature measurements were available from 8 internal and external sensors, previously installed in the tower as part of a static monitoring system.

As no structural changes were detected in static monitoring, the main objectives of this second case study was to investigate the different performances of the dynamic regression models in removal/minimizing the environmental effects on modal frequencies, when more than one external temperature sensor is available.

PEDESTRIAN-FOOTBRIDGE DYNAMIC INTERACTION: UNCOUPLED ANALYSIS USING A MSD MODEL

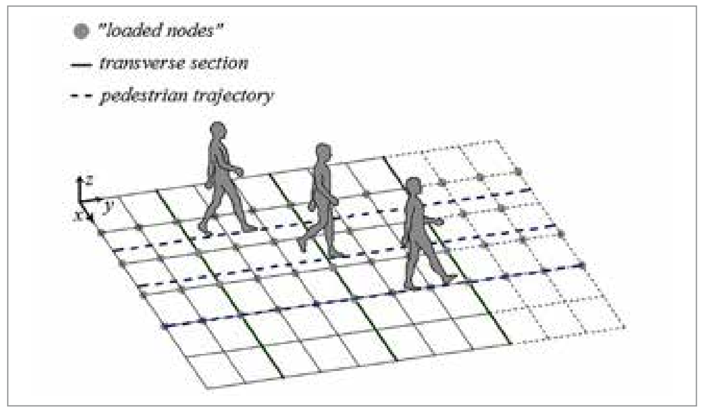
Eleonora Lai – Supervisor: Prof. Maria Gabriella Mulas

In the last years, the need for structures able to link the functional and aesthetic role has led to the design of new flexible footbridges characterised by a low ratio between permanent and variable loads making them more sensitive to dynamic loads, such as the forces transmitted by pedestrians.
During the human walking, the pedestrian moves on a flexible structure adapting his gait to the bridge motion. The interaction between pedestrian and footbridge takes place at the contact points, where the pedestrian transmits contact forces to the bridge that, in turn, imposes a set of displacements and velocities to the pedestrian's feet. In the straightforward approach to the problem, both systems should be described as mechanical systems, having proper mass, stiffness and damping matrices. In fact, only the description of the human being as a mechanical system allows for the derivation of the equation of motion of the bridge-pedestrian coupled system. In the light of above, in this work a large effort has been devoted to the analytical formulation of a walking human-body mechanical system. A new bipedal pedestrian mechanical model is proposed, to the aim of providing a simple SDOF system (Fig. 1) able to satisfy two main requirements. First of all, the



1. Single DOF system model of a human being

model must reproduce the human locomotion, incorporating both the single and the double support phases. Secondly, its equation of motion must take into account both the interaction with the bridge and the biomechanical force acting on it. The theoretical formulation of the HSI interaction involves the derivation of the bridge-pedestrian coupled equations of motion accounting for all the relevant phenomena involved. Bridge and pedestrian are described with a finite number of DOFs. Due to the pedestrian motion, the structural matrices of the coupled system are time-dependent and should be modified whenever the pedestrian's foot position on the bridge changes. The proposed alternative solution strategy is based on the forced uncoupling of the system, based on the key assumption that the contact points between pedestrian and bridge deck are massless. The uncoupled formulation considers the footbridge and the pedestrian as two separate sub-systems, reducing the computational burden associated to the time-varying properties of the matrices of the coupled system. Moreover, different mechanical systems can be adopted to model the pedestrian, without modifying the analytical formulation. A staggered solution, iterative in principle, is adopted to integrate the uncoupled equations.
The analytical procedure has been implemented in a numerical code, named INTER2.0, able to consider the pedestrian as a dynamic force or a mechanical system. In the numerical implementation, the bridge is modelled using a commercial code, with the FE method, and the bridge geometry is considered correctly without any approximation. The program reads in input both the bridge structural matrices and the pedestrian dynamic properties needed to assembly the MSD matrices or the feet forces. The FE element approach for the bridge modelling adopted in the uncoupled formulation enables to consider both different pedestrian's models (force or mechanical system) and type of bridges. Thus, INTER 2.0 should be seen as a general purpose code and a useful tool to study the HSI between a footbridge and pedestrians.
In more detail, the code can consider groups of pedestrians having different spatial configurations, degree of synchronization, dynamic properties and step frequencies. The pedestrians can freely walk following a rectilinear trajectory parallel to the bridge axis, with a x_p coordinate inside the deck grid (Fig. 2). Thus, in general the pedestrian position does not coincide with a mesh node. To overcome this problem, a set of proper shape functions (SFs) is introduced to transform the contact forces into equivalent nodal loads. The SFs ae a function of the pedestrian's position *x(t)*, and are governed by the pedestrian's movement algorithm. Furthermore, the inter-variability, in terms of step frequency, is taken into account through a probabilistic model able to correlate the pedestrians on the bases of their mutual distance.
The case study adopted in this work is a suspended footbridge in Seriate (Italy), whose dynamic properties were identified through an experimental campaign also encompassing the structural response under the crossing by different groups of pedestrians.
In this thesis a bridge FE model has been developed, based on the as-built design data. A non-linear static analysis has been performed to take into account the additional geometric stiffness matrix which, added to the elastic stiffness matrix, gives the total stiffness. A numerical procedure has been proposed to determine the fictitious temperature increments simulating the pre-stressing effects on the suspension system. At the end of the non-linear static analysis, a modal analysis has been performed. The correlation between experimental and numerical modal parameters turned out to be fully satisfactory. The agreement between experimental and numerical bridge response under moving pedestrians has validated the analytical formulation. Numerical analyses have addressed the effect, on the bridge response, of a few parameters: distance between pedestrians, correlation in terms of step frequency and spatial distribution. The results due to groups of pedestrians walking along different eccentric trajectories have highlighted the relation between the bridge mode excited and the pedestrians' position. Furthermore, the importance of the frequencies correlation and its dependence on the people configurations have been studied, comparing the bridge accelerations due to a group of pedestrians, having step frequencies either correlated or uncorrelated and different spatial configurations (uniform grid and pseudo-random grid). Several groups of pedestrians perfectly correlated (same frequency and synchronization) have been considered to account how the people affect the bridge damping. The numerical outcomes confirmed literature results.



2. Pedestrians' trajectory

REPLACEMENT BEAM METHODS IN ANALYSIS OF TALL BUILDING STRUCTURAL SYSTEMS

Hadi Moghadasi Faridani - Supervisor: Prof. Antonio Capsoni

Global analysis of building structural systems can be exerted at two levels: complete model analysis and condensed model analysis. Despite static and dynamic analyses of the complete model of building structures can be nowadays easily afforded with the aid of commercial FE packages, the adoption of such an approach since an early stage of a design process may be time consuming and sometimes can lead to a constrained definition of the concept. On the opposite, using appropriate condensed models can help both researchers and designers to more properly deal with the analysis and design of structures. One of the most extensively used condensed systems is the continuum model, which idealizes a building system with an appropriate replacement beam. This simplified method can provide a tool for framing the first design phases and to check the outcomes of the computer-based analyses; moreover, it helps practitioners understand the complex behavior of large structures such as tall buildings. In this research, a literature survey on continuum-based methods for building analysis is carried out firstly. Then, a novel replacement beam model, which takes into account all the deformation modes of building systems, is proposed and characterized by appropriate stiffness relations. A one-dimensional FE formulation is developed for the numerical solution of the model and used in assessment of static responses, eigenproperties, and forced dynamic responses of several building structures. Afterwards, two replacement beam models are developed to idealize coupled shear walls; meanwhile, they are employed to be further generalized for dynamic applications. The analytical solution of static responses and an appropriate FE formulation are then presented for the models. Using a discrete system of coupled shear walls, the distributed internal viscous damping (DIVD) of Kelvin-Voigt type with the bending and shearing mechanisms is introduced and theoretically established. Based on this discrete system with multi-damping effects, three continuum-based models are developed, whereas they are appropriately consisting of suitable kinematical fields and damping mechanisms. Using the FE technique, all the discrete and continuum models are formulated; moreover, a closed-form solution is developed for one of the continuum-based models consisting of a single displacement field. In this research, it is theoretically explained how passive dampers with various installation configurations can be modeled by a continuous damping mechanism through the replacement beams. The optimization problem of passive damping is then pursued, resulting in definition of a non-uniform equivalent shear damping. Further applications of continuous damping models acted upon by replacement beams are discussed. To this end, using a simple continuum-based model, some physical damping models are appropriately identified with wind and seismic applications. All the numerical and analytical models proposed in this research are properly implemented and verified consequently. As a general conclusion, the proposed continuum-based models can be potentially useful for the design and analysis of buildings, at the least in the preliminary stage of structural design.

CONSTITUTIVE MODELLING OF THE SOLID-TO-FLUID TRANSITION IN GRANULAR MATTERS

Irene Redaelli - Supervisor: Prof. Claudio Di Prisco

In nature, very rapid landslides are very common. In the scientific literature, quite numerous are the case histories testifying their catastrophic potential.
The objective of reducing the vulnerability of the territory passes through the possibility of simulating/reproducing these events. The computational analysis of these natural phenomena is quite challenging, since the numerical tool has to account for large displacements, large strain rates and hydro-thermo-mechanical processes. For this reason, in the numerical simulations, the inception and the evolution of the gravitational movement are usually tackled separately, by employing different numerical approaches and different constitutive models.
From a physical point of view, in the last decades, many authors have observed, at the microscale level, that two possible dissipative mechanisms of interaction among particles are possible in granular flows: enduring contacts among grains, which are involved in force chains, and nearly instantaneous inelastic collisions. When strain rates are small, the first mechanism prevails and the material behaves like a solid (quasi-static regime). The entire network of contacts has to be continuously rearranged. The energy is mainly stored as elastic energy and dissipated through frictional enduring contacts. On the other hand, when the medium is dilute and deformations are rapid, particles interact only through collisions; the material response can be assimilated to that of a gas (collisional regime) where the energy is dissipated through inelastic collisions and stored as kinetic fluctuating energy. When the grains interact both through force chains and through collisions, the material is in a sort of transition regime and behaves like a fluid.
The objective of this contribution is to develop a constitutive relationships suitable for being used to simulate the mechanical response of granular materials under both quasi-static and flowing conditions, when the material experiences a sort of solid-to-fluid phase transition: stresses are assumed to be obtained by linearly adding a collisional and a quasi-static contribution. The first contribution stems from the kinetic theory of granular gases. For the latter contribution, an elasto-plastic-strain-hardening model incorporating the critical state concept is adopted. The transition from solid-like to fluid-like conditions is therefore assumed to be governed by the granular temperature and the void ratio, the unique state variables of the model.
According to this unifying constitutive model, the total energy provided to the material point can be elastically stored, transported under the form of grain agitation, dissipated by the soil skeleton (i.e. force chains) and by the collisions among grains. The collisional state is characterized by the nullification of the elastic stored energy and the quasi-static solid state by the nullification of the agitation energy. In contrast, steady state conditions correspond to constant value of both the elastic and kinetic fluctuating transported energy. The evolution of the granular temperature is governed by the balance of the kinetic fluctuating energy.
The model is based on the definition of four distinct unsteady regimes: the visco-elastic, the visco-elasto-plastic, the critical and the collisional. Each regime is characterized by the fulfillment of suitable mechanical conditions. In particular, under critical regime, the void ratio evolution is governed by the mean quasi-static pressure via the critical state locus definition. This implies that the plastic volumetric strain rate does not obey the flow-rule but is computed by depurating the total volumetric strain rate of the elastic component.
Steady state conditions can be achieved under critical and collisional regimes.
The originality of the approach proposed, derives from the interpretation of the critical state as a peculiar steady state taking place under quasi-static conditions, when the granular temperature approaches a zero value.
The visco-elasto-plastic constitutive relationship is integrated under both constant pressure and constant volume conditions. Simple shear and true triaxial loading and unloading conditions are considered in order to test the capability of the model of taking into account the dependence of the mechanical behaviour on the initial void ratio, the imposed mean pressure and, in particular, the imposed deviatoric strain rate, under both steady and unsteady conditions.
The introduction of the elasto-plastic rotational hardening within the quasi-static contribution, allows to reproduce satisfactorily the real behaviour of granular materials sheared under quasi-static conditions. In fact, the elasto-plastic softening its particularly important since it facilitates the onset of strain localization within the continuum, which is the basis of the triggering of the landslide phenomenon.
The characteristics described above, make this model a very promising tool which is applicable not only to the simulations of flow like landslides, but also for the evaluation of the impact force of granular materials on structures and for the simulations of granular flows in general. In fact, the simulation of granular flows is important also for the large numbers of industrial processes and applications, such as the transport of seeds, rice, corns, sugar, coffee, pills, powders, rocks as well as the motion of blood cells in small vessel.

ON THE LOAD INDUCED THERMAL STRAIN FOR PLAIN AND STEEL FIBER REINFORCED CONCRETE SUBJECTED TO UNIAXIAL LOADING

Thomaz Eduardo Teixeira Buttignol - Supervisor: Prof. Marco Di Prisco

Concrete structures exposed to high temperatures are submitted to a complex hydro-physical-chemical transformation, which leads, among others, to concrete drying (water evaporation) and dehydration (physically and chemically bound water evaporation from the CSH layers in the cement paste), microcracking due to thermal mismatch and aggregates increasingly ductile behavior as a result of geomechanical properties decay. Moreover, during heating, preloaded structures on the elastic phase are subjected to additional mechanical deformations, which is attributed to transient creep.
Transient creep is the irrecoverable deformation that occurs in concrete structures as a result of the application of a sustainable load during heating. It is seated in the cement paste and is the result of concrete drying and dehydration. At elevated temperatures, transient creep is accelerated by the aggregates degradation. Since transient creep is coupled with other mechanical strain components (elastic-recoverable and plastic-irrecoverable), it is commonly studied indirectly by means of the so-called load induced thermal strain (LITS), which is the difference between concrete strains of unloaded and loaded structures, disregarding the initial elastic deformation. Hence, LITS takes into account transient creep and also irrecoverable mechanical strains, changes in the elastic strain due to the high temperature and thermal expansion restraint imposed by the boundary conditions.
Said that, five key issues were studied, i.e., SFRC material mechanical properties evolution due to long term aging, the contribution of the aggregates to LITS considering different concrete types, the effect of the age of loading to LITS, the path dependence and the development of a new LITS semi-empirical model.
The thesis is divided in three main parts, respectively focusing in the experimental, theoretical and numerical aspects of LITS in concrete structures. In the first part, the mechanical characterization of the material is carried out in order to observe the change in material mechanical properties, especially the residual post-cracking tensile strength, due to long-term aging. For this purpose, flexural tests together with indirect tensile tests by means of Double Edge Wedge Splitting (DEWS) procedure were developed. A comparison between 4PB tests at 1 year and 10 years is carried out, demonstrating a pronounced increase in the peak and in the serviceability limit state (SLS) residual strengths, followed by a relatively small increase in the ultimate limit state (ULS) residual strength. The material classification according to fib Model Code 2010 of 1 year old and 10 years specimens is developed in order to observe possible changes in the material class through the years. The tensile constitutive law is obtained according to fib Model Code 2010 and a plane section (PS) numerical analysis in bending is developed applying the constitutive law of the material obtained from the material class. The numerical results are compared with the bending tests, showing the reliability of the PS analysis and the effectiveness of the back analysis method to identify FRC tensile post-peak response.
In the second part, the contribution of the aggregates to LITS in different concrete types is studied. and a new LITS model is proposed, recognizing concrete as a heterogeneous biphasic material (aggregates + matrix). The semi-empirical model is based on two variables, dependent on the aggregates and cement content, and two compliance functions dependent on the temperature and corresponding to concrete thermomechanical (microcracking, aggregate degradation and thermal expansion restraint) and thermochemical (concrete drying and dehydration) properties.
The model is compared with experimental results obtained in literature and with other empirical models, demonstrating its reliability.
In the third part, a 2D three-phase mesoscopic analysis is developed, as shown in Figure 1. A parametric analysis is carried out in order to validate the numerical model and observe its sensitivity due to different aggregate distributions and variations on the mechanical properties of the concrete phases (matrix, inclusions and interfacial transition zone). The path dependence is analyzed on preloaded and preheated specimens in order to observe the effects of the boundary conditions on LITS. Moreover, LITS was uncoupled into dehydration strain, aggregate strain and mechanical strain (thermal expansion restraint due to the applied load). The results demonstrated that concrete thermal expansion restraint plays a very important role both to the total deformation and to LITS. A comparison between the numerical and analytical results was performed in order to further validate the new LITS analytical model.

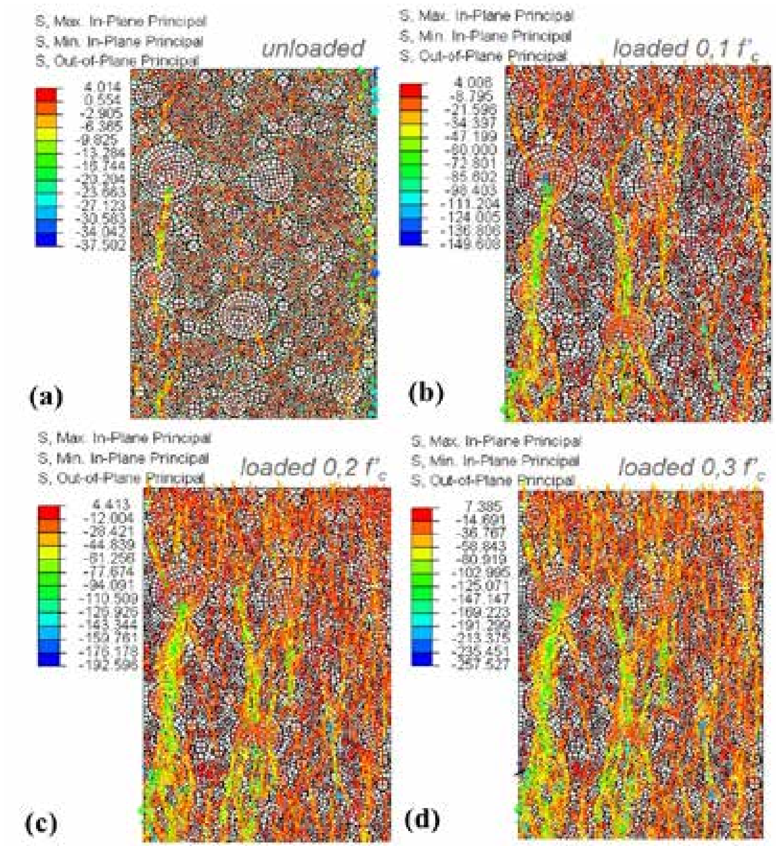


Figure 1 – Principal stresses for (a) unloaded and loaded specimens at (b) $0{,}1 \cdot f_c$, (c) $0{,}2 \cdot f_c$, (d) $0{,}3 \cdot f_c$

1. 2D three-phase mesoscopic analysis

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