INFORMATION TECHNOLOGY | INTERIOR DESIGN | MANAGEMENT, ECONOMICS AND INDUSTRIAL ENGINEERING | MANUFACTURING AND PRODUCTION SYSTEMS | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING | MECHANICAL SYSTEMS ENGINEERING | PHYSICS | PRESERVATION OF ARCHITECTURAL HERITAGE | PROGRAMMING, MAINTENANCE, REHABILITATION OF THE BUILDING AND URBAN SYSTEMS | RADIATION SCIENCE AND TECHNOLOGY | ROTARY WING AIRCRAFT | SANITARY - ENVIRONMENTAL ENGINEERING | **STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING** | TECHNOLOGY AND DESIGN FOR ENVIRONMENTAL QUALITY IN BUILDINGS AND URBAN CONTEXT | TERRITORIAL DESIGN AND GOVERNEMENT | URBAN AND ARCHITECTURAL DESIGN | VIRTUAL PROTOTYPES AND REAL PRODUCTS | WATER ENGINEERING | AEROSPACE ENGINEERING | ARCHITECTURAL COMPOSITION | ARCHITECTURE, URBAN DESIGN, CONSERVATION OF HOUSING AND LANDSCAPE | BIOENGINEERING | BUILDING ENGINEERING | DESIGN AND TECHNOLOGIES FOR CULTURAL HERITAGES | ELECTRICAL ENGINEERING | ENERGY | GEOMATICS AND INFRASTRUCTURES | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INDUSTRIAL DESIGN AND MULTIMEDIA COMMUNICATION |

PhD Yearbook | 2010

Chair:
Prof. Pietro Gambarova

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, 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 helpful in solving the problems typical of other technical-scientific domains, whenever understanding and controlling the mechanical aspects are necessary to guarantee 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; and (d) biomechanics, that is a key aspect of industrial bio-engineering. 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, Geotechnical and Bio-Mechanical Engineering.

Contents of the Doctoral Program

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 public and private industry, designers and institutions dealing with structural safety and reliability, as well as for the environmental impact of the constructions.

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 study plan (180 credits) is divided into 4 phases:

1. Propaedeutic formation (0-20 credits, 1st year), based on courses borrowed among the MS courses ("Laurea Magistrale"), with the objective of giving a common scientific basis to the PhD Candidates coming from different schools.
2. Basic, research-oriented formation (40 credits, 1st and 2nd years) consisting of 5-credit courses to be taken by the Candidates, to complete and enrich their scientific formation. These courses are focused on the most relevant topics debated within the scientific community, in the domains of materials and structural mechanics, structural dynamics and seismic engineering, soil mechanics and research management.
3. Specialized, research-oriented formation (10-30 credits, mostly in the 2nd year), based on a variety of opportunities offered to the Candidates: (a) short courses, and (b) series of seminars given by either internal or external faculty members, as well as by researchers from the industry, from the Society of the Engineers and from public institutions; and (c) short courses offered by well-known scientific institutions, like CISM – Int. Center for Mechanical Sciences (Udine, Italy), IUTAM – Int. Union of Theoretical and Applied Mechanics (Summer Schools in different European countries), Rose School (Pavia, Italy) and JCR – Joint Research Center (Ispra - Varese, Italy). The Candidates are also suggested to attend the short courses organized by other Doctoral Schools, at the Politecnico or at nearby universities (Politecnico di Torino, Universities of Genoa and Brescia ...).
4. PhD Dissertation (110 credits), whose preparation (in English) is a pre-requisite for being admitted to the final examination. The dissertation should contain original results concerning relevant and actual engineering problems, with reference to basic topics or to applications and technology. The preparation of the dissertation consists of different phases, whose results are presented by each Candidate at the end of the 1st, 2nd and 3rd year, in specific workshops, open not only to the Faculty and to the PhD Candidates, but also to the members of the Advisory Board and to all interested scholars.

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

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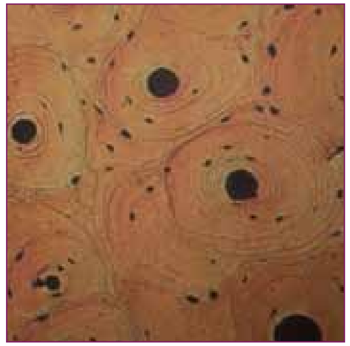
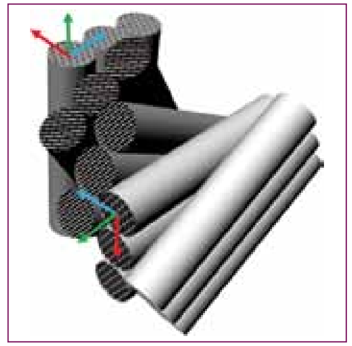
ORIENTATION AND LENGTH-SCALE DEPENDENT MECHANICAL PROPERTIES IN LAMELLAR BONE AT THE MICRO AND NANOSTRUCTURAL HIERARCHICAL LEVELS

Davide Carnelli

Anisotropy is one of the most peculiar aspects of cortical bone tissue mechanical behavior; however, since cortical bone is a hierarchically structured material, its anisotropic mechanical behavior is a concept that should be treated only with strict relationship to the length scale of investigation. Lamellar bone anisotropy may arise from the inherent anisotropy of the mineralized collagen fibrils as well as to their geometric arrangement known as rotated plywood structure. In this light, cortical bone tissue exhibits a mechanical and structural anisotropy, owed to both the mechanical anisotropy of its constituents and to the pattern in which these constituents are arranged.
Due to the tissue hierarchical structure and to the characteristic length of each hierarchical level, the anisotropy of lamellar bone in the osteonal structures is expected to be length scale dependent and to undergo homogenization effects. In this light, investigation of mechanical properties of lamellar bone should be performed at multiple hierarchical levels.
Instrumented indentation is a valid method to measure mechanical properties of bone tissue at various structural levels. The determination of mechanical properties of bone from nano or micro indentation experimental tests should be performed by carefully considering at least two main factors: hierarchical arrangement of constituents and anisotropy of the material response. Indeed, indenting at different penetration depth allows evaluating the mechanical properties of the tissue spanning its structural features at multiple length scales; whereas, indentation along different directions may allow for anisotropic response of the tissue.
The numerical approach can be successfully used to investigate aspects of bone tissue mechanics that analytical methods solve in approximate way or do not cover. At the present time not all the features of experimental response of the tissue are correctly simulated by the most common finite element models, and accurate predictions of direction-dependent indentation moduli, direction-dependent hardness, and negligible pile up simultaneously still remain a challenge. Therefore, it is of particular interest to establish a relationship between the peculiar aspects of bone tissue response during an indentation test and the constitutive parameters ruling the inelastic behavior of the bone tissue.
In this work, experimental and computational approaches are employed to investigate the orientation and length-scale dependent mechanical properties at the micro and nanostructural hierarchical levels in lamellar bone tissue.
Knowledge of the tissue mechanical properties at multiple length-scales was achieved by testing the same osteonal structure at different penetration depths and along two orthogonal orientations.
The hierarchical arrangement of lamellar bone was found to be a major determinant for modulation of mechanical properties and anisotropic mechanical behavior of the tissue. The effect of length scale on lamellar bone anisotropic mechanical behavior and the critical length at which homogenization of the mechanical properties occurs were determined by measuring the spatial modulation of indentation response. The structural anisotropy and mechanical modulation associated to the lamellar structure are consistent with the hypothesized capability of the tissue to act as a protective mechanism which opposes cracks propagation at the lamellar level.
An analytical model valid for laminate composites which considers the inherent anisotropy of the mineralized collagen fibrils was applied to the experimental test results at the highest spatial resolution. The elastic constants for a sub-layer of mineralized collagen fibrils within an osteonal lamella, determined on the basis of the spatial arrangements of the fibrils, were found to be consistent with an analogous set available in the literature.
The numerical approach was used to develop a finite element model which allows for anisotropic elastic and post-yield behavior of the tissue. The constitutive model for the post-yield behavior included a tension-compression mismatch and a direction dependent yield stress. Indentation experiments along the axial (corresponding to the long bone axis as well as osteonal axis) and transverse (normal to the osteonal axis) directions were simulated. The developed model is able to predict direction-dependent indentation moduli, direction-dependent hardness, and negligible pile-up of the material simultaneously. The yield locus anisotropy resulted to be necessary to predict the direction-dependent hardness, while it was found to be less important to predict the direction-dependent indentation moduli. A small inelastic volumetric strain and friction between tissue and indenter played a key role in addressing the experimental evidence of negligible pile-up.



1. Optical microscopy image of bovine cortical bone tissue osteonal microstructures in the axial direction with respect to the bone long axis. Magnification is 200x



2. Schematic illustration of the rotated plywood structure representing the organization of the collagen fibrils and the plate-shaped hydroxyapatite crystals in a lamella of osteonal bone

Direct comparison between the experimental and simulated indentation tests evidenced a good agreement also in terms of peak load and loading-unloading indentation curves for a transverse to axial yield stress ratio comparable to the experimentally obtained transverse to axial hardness ratio.
The structural complexity of bone tissue requires that the assessment of its mechanical properties involves multiple hierarchical levels, from the macroscopic scale down to the micro and nanostructural level till the most basic components. Understanding structure-property relationships and the effects of structural features on the biomechanical properties of bone would enable not only the development of more accurate models for analysis of implants and potential bone-replacement materials, but also the progress in designing bio-inspired structural materials which take advantage of the mechanical design principles found in nature.
These latter topics undoubtedly represent fascinating long-term scientific goals in the materials science and engineering field.

HIGH STRAIN-RATE UNIAXIAL TENSILE CONSTITUTIVE BEHAVIOUR IN FIBRE REINFORCED CEMENTITIOUS COMPOSITES

Alessio Caverzan

Fibre-reinforced cementitious composites were developed starting in the eighties when their ability in energy absorption was first highlighted. The increasing relevance of the problems related with the damage of socially-sensitive structures (e.g. as high-rise buildings, bridges, and tunnels) has led to the study of fibre-reinforced composites also under fire and blast conditions. In the present framework, a research aimed at giving a contribution to the understanding of the behaviour of advanced fibre-reinforced cementitious composites subjected to low and high strain rates, as well as, exposed to high temperatures, was designed. A wide experimental investigation was carried out both in static and dynamic fields, and the results are compared.

In the whole research a high performance cementitious composite optimized with steel fibres (HPFRCC) has been taken into account. Steel fibres were high carbon straight fibres, 13 mm long with a 0.16 mm diameter (aspect ratio l_f/d_f equal to 80); their content was equal to 100 kg/m^3. The maximum aggregate size was equal to 2 mm. The HPFRCC obtained had a compressive strength (f_c) equal to 115 MPa.

First, tests at low strain rates were performed to characterize the material from the static point of view. Particular attention was turned to the investigation of the effects of the increasing temperature and of the casting procedures. Static tests were carried out on notched samples and on unnotched samples. The unnotched beam samples were cast in order to identify the material behaviour in bending at room condition and after thermal treatment. Samples were all extracted from a slab 1.6 m x 0.60 m in plane, 30 mm thick. The slab was cast by applying a unidirectional flow. In order to guarantee a certain fibre orientation the proprieties of the self compacting material were used taking advantage of the flow direction. Temperature influence was then studied for the unnotched samples by thermally treating the specimens prior to testing up to a temperature of 200°C, 400°C, and 600°C, respectively. In order to perform the mechanical characterization of the material according to National Recommendations (UNI11039) three prismatic notched samples were cast. Specimens were 150 mm x 150 mm cross-section and 600 mm long. Due to the high viscosity of the material at fresh state, it was not possible to cast them as suggested by the code, but they were cast in steel formworks by applying a flow at right angle with the longer formwork side obtaining a fibre random distribution. Both the unnotched and the notched beam samples were tested on bending. Finally, the bending and the uni-axial response of the materials were compared by performing uniaxial tensile tests on cylinders sampled from the bent specimens. With reference to the material self compacting properties, a good fibre alignment was obtained by imposing a unidirectional casting flow. This result is confirmed by the low scatter observed in the material response. A low scatter was observed in the overall test series carried out (bending tests and tensile tests carried out on samples with a good fibre orientation), and at all the strain rates investigated. The material so cast, and thus characterised by a good fibre alignment, showed a very high performance compared with other cementitious composites at comparable costs. The comparison between the results obtained from the material with a good fibre orientation and those from the material characterised by a random fibre distribution, pointed out the influence of boundary conditions (e.g. cast procedure). Boundary conditions in the structural manufacturing process were shown to dramatically change the material response. Hence, it is needful to characterize the material behaviour by exploiting appropriate tests and specimens. The advanced fibre reinforced cementitious composites are usually considered as convenient when a significant reduction of the structural weight can be obtained. Thin structures are the first and most important application of these innovative materials. However, it is recalled that particular attention must be turned to the tests used to characterise the material behaviour. Exploiting standardised samples could in fact lead to a not correct evaluation of the material behaviour. For these reasons a "structural" sample, which is strictly related to the structure considered and to the boundary conditions adopted during casting operations, should be used to define the material behaviour. The static characterisation of the material highlighted a good response also at high temperatures; a bending hardening behaviour was shown also when previously heated up to 400°C. Though at 600°C the material performance is significantly reduced, a tensile strength of 15 MPa is however measured. The material behaviour at 600°C shows a strongly softening behaviour and fails due to fibre rapture. This change in the material response is assumed to be caused by the degradation of the physic-mechanical properties of the fibres. This was confirmed by tests on the steel wire used to produce the fibres, which highlighted that at 600°C the microstructure of the material changes. The resistant cross sectional area of the wire reduces, favouring the development of an oxide film on its lateral surface, and leading to a decrease in its strength of 75%. The material was then characterised also from the dynamic point of view. Samples, always sampled following bending tests, were tested under intermediate strain rates (0.1-1 s^{-1}) with a hydro-pneumatic machine. On the other hand, high strain rates were studied by exploiting a modified Hopkinson bar (MHB) present in the DynaMat laboratory of the University of Applied Sciences of Southern Switzerland of Lugano. The MHB consists of two circular aluminium bars, called input and output bars (with a diameter of 20 mm and having length of 3 and 6 m, respectively) between which the HPFRCC specimen is glued using a bi-component epoxy resin. The input bar is connected to a high strength steel pretension bar (having 6 m length and 12 mm diameter), used as pulse generator. A test with the MHB is performed as follows:

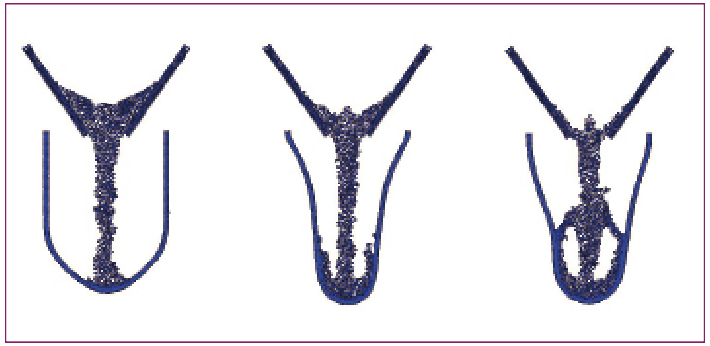
- **a.** first, a hydraulic actuator (of maximum loading capacity of 600 kN) pulls the high strength steel bar; the pretension stored in this bar is assured by the blocking device;
- **b.** the second operation is the rupture of the fragile bolt in the blocking device, which gives rise to a tensile mechanical pulse of duration 2.4 ms and with a linear loading rate during the rise time. The pulse then propagates along the input and output bars, leading the specimen to failure.

Comparison between static and dynamic tests was then performed allowing to highlight several relevant aspects. First, at room temperature the comparison between static and variable strain rate tests, carried out by means of three different mechanical devices, exhibits high values of the Dynamic Increase Factor. For strain rates up to 0.1 s^{-1} the tests results seem to be well predicted by the trend proposed in the Model Code 2010 for plain concrete. Nonetheless, the DIF values for HPFRCC start to increase at a lower value of the strain rate (between 0.1 and 1 s^{-1}) than that suggested by different models (1 s^{-1} for Malvar and the Model Code 2010, 30 s^{-1} for the Model Code 1990). Between 1 and 150 s^{-1} a transition zone with a lower slope with respect to that expected for a plain concrete was observed. By increasing the strain rate up to 300 s^{-1} the DIF increases, but the models considered overestimate the slope also in this range of strain rates. On the other hand, analysing DIF behaviour at increasing temperatures allowed to highlight that it is not substantially influenced up to 400°C. On the contrary, at 600°C a high increment in the values of DIF was observed with particular reference to strain rates of 150 s^{-1}. At higher strain rates (300 s^{-1}) this parameter decreases as a function of the magnitude of the previous thermal treatment.

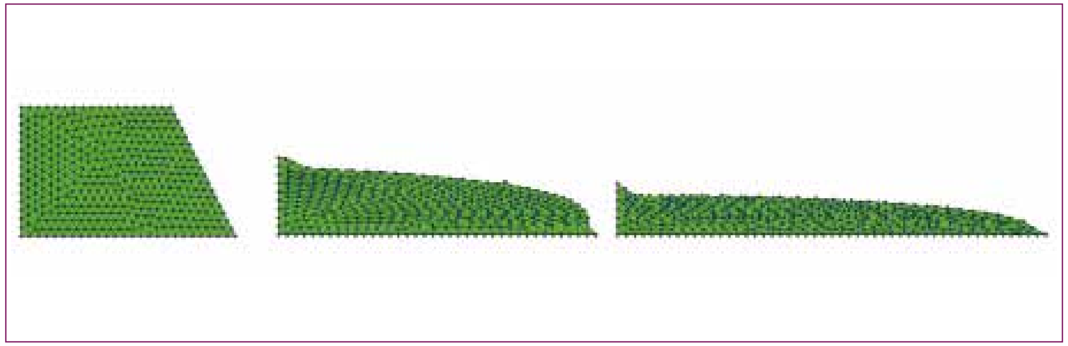
A LAGRANGIAN FINITE ELEMENT METHOD FOR THE INTERACTION BETWEEN FLEXIBLE STRUCTURES AND FREE SURFACES FLUID FLOWS

Massimiliano Cremonesi

The numerical simulation of fluid-structure interaction phenomena is increasingly important in many fields of engineering. The computational treatment of the free surface and of the interface between solid and fluid in fluid-structure interaction is always critical. The Arbitrary Lagrangian Eulerian method (ALE) in which the movement of the fluid particles is independent from that of the mesh nodes, is often used to solve these kind of problems. Other possible methods are based on the volume of fluid or level set algorithms. Meshfree and meshless methods are often used for their ability to recover the free-surfaces and the interfaces. A possibility to overcome the difficulties concerning the tracking of the interfaces is to adopt a Lagrangian approach for both fluid and structure. In the present work a fluid-structure interaction algorithm is presented based on a staggered approach in which the fluid is treated in a Lagrangian framework using a new implementation of the so called Particle Finite Element Method (PFEM), first proposed by Oñate, Idelsohn and coworkes, and the structure using a classical finite element method.
An advantage of the Lagrangian approach for the fluid flow is that the convective terms in the momentum conservation disappear. The difficulty is however transferred to the necessity to frequently regenerate the mesh. In fact, if a fixed finite element mesh is used and the position of element nodes is updated as a consequence of the fluid flow, very soon the element distortion becomes excessive.
A remedy which allows to avoid these distortions consists of systematically remeshing the volume of the problem.
To this purpose, an efficient Delaunay triangulation has been adopted. Moreover to define the integration domain and to correctly impose the boundary conditions a method to identify the external boundary is necessary. This has been achieved using a criterion based on the mesh distortion called *alpha shape method*. The same method allows to define the inclusion and the separation of the individual particles.
When remeshing is performed, data have to be transmitted 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 are used, so that only linear shape functions can be used for both velocity and pressure. However, it is well known that this type of discretization does not satisfy the *LBB inf-sup compatibility condition* and so a stabilization method is required. To this purpose a *pressure-stabilizing Petrov-Galerkin* (PSPG) stabilization is used.
The proposed Lagrangian Finite Element Method is particularly suited for the solution of fluid-structure interaction problems in the presence of free-surfaces, in conjunction with a classical finite element method for the solid part. A critical issue of fluid-structure interaction schemes is the identification of the contact interfaces between the solid and fluid domains. The evolution of the interaction surfaces is tracked using a novel algorithm which exploits the features of the Lagrangian approach based on the continuous remeshing introduced for the fluid solution. The proposed algorithm is based on the superposition of a set of fictitious fluid particles to the nodes of the solid domain, which can come in contact with the fluid domain. When the Delaunay triangulation is performed, the alpha-shape criterion selects those parts of the interface where the fluid particles can possibly come into contact with the structure. If the two discretized domains are not in contact, the fluid and the solid analyses are performed separately without any interaction. If instead parts of the two discretized domains are in contact, a coupled analysis is performed with a Dirichlet-Neumann iterative approach.
The proposed scheme has been applied to both Newtonian and non-Newtonian fluids. Comparisons with numerical benchmarks and with experimental results are presented to show its potentialities and to find possible defects. Figure 1 shows an example of a fluid-structure interaction problem involving large fluid motions with large displacements of the structure, solved with the present approach. Under the action of the gravity force a fluid drops down from a funnel-shaped rigid container into a thin elastic container for which a linear elastic constitutive law is assumed to hold. Figure 1 shows the deformation of the elastic container at different time step.
The non-Newtonian solver has been also used to simulate typical tests on fresh concrete, mortar and cement pastes.
In general, yield stress and viscosity are parameters used to characterize the workability of this kind of materials. The experimental determination of these parameters is a research topic of recent years. However, in the identification of parameters an efficient numerical tool can be also very useful. To this purpose, the non-Newtonian solver based on the Lagrangian finite element approach is used to simulate typical tests widely used in the experimental identification of the rheological properties of fresh cement paste and concrete, showing a good agreement between numerical and experimental results. Figure 2 shows a typical slump flow test.



1. Deformation of an elastic container. Snapshots at different time step

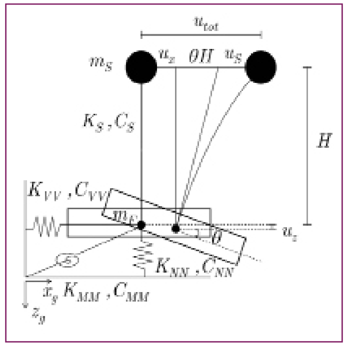


2. Mini-slump-flow test. Snapshots at different time steps for a cement paste

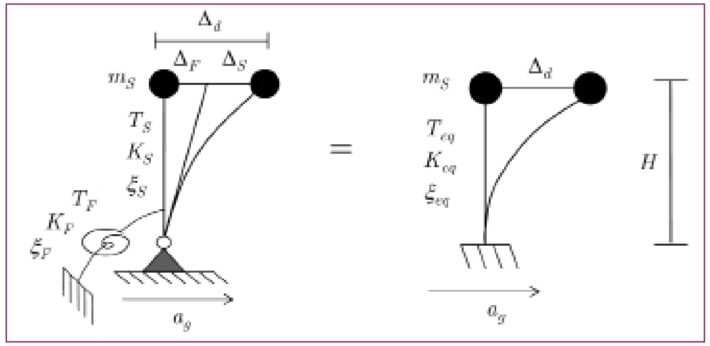
NON-LINEAR DYNAMIC SOIL-STRUCTURE INTERACTION: APPLICATION TO SEISMIC ANALYSIS AND DESIGN OF STRUCTURES ON SHALLOW FOUNDATIONS

Raffaele Figini

The thesis deals with the non-linear dynamic soil-structure interaction problem during earthquakes. Namely, reference is made to seismic analysis and design of structures resting on shallow foundations.
The engineering motivation arises from the recent development of performance based design approaches, aiming at characterizing the structural behaviour in terms of displacements, rotations, distortions and drifts performance rather than in terms of strength criteria. Since both structure and soil-foundation can be potential sources of non-linearities and energy dissipation during a strong earthquake, they should be both characterized by non-linear models, allowing to capture their complex non-linear interaction, and giving a reliable estimate of system displacements, both at the foundation and at the super-structure level.
The first part of the thesis contains a review of previous analytical and experimental works. First, a review of different non-linear soil-structure interaction modelling approaches is presented. Finite element models as well as Winkler-based models are briefly described, underlining their advantages and disadvantages with respect to their accuracy and computational costs. The focus is then pointed on macro-element models, which are described in more detail, since this approach is the one chosen to characterize soil-foundation non-linear response throughout the work. Subsequently, an extensive overview is presented of available experimental results from large scale cyclic and dynamic tests performed on shallow foundations. The salient features of the response are highlighted, such as the effect of uplift and the permanent induced vertical settlements and rotations.
The second part of the work concerns numerical modelling. A macro-element model for cyclic and dynamic description of shallow foundations is developed, starting from two existing macro-element formulations. Original features and differences with respect to these previous models are discussed, as well as the modelling of different types of soil-foundation non-linearities. The model is then validated based on available experimental data. At the end of the model validations, a standard set of parameters is introduced, which can be used for predictive analyses performed by the proposed macro-element. Then, a numerical tool based on this macro-element is developed to perform non-linear dynamic time history analyses, and validated as well on experimental results. An original feature is represented by the implementation of non-linear constitutive models also for the super-structure, so that both the structure and the soil-foundation system can develop non-linearities.
The structure is modelled by a non-linear 1 degree-of-freedom (dof) oscillator, extended for some applications to multi dof, while the foundation by a 3 dof macro-element (Fig. 1). It is worth noting that structural earthquake engineers have traditionally developed numerical tools which model sophisticatedly the structure, but which treat soil-structure interaction only by means of linear visco-elastic springs. Conversely, geotechnical earthquake engineers usually model sophisticatedly the soil-foundation system, but consider linear elastic super-structures. The possibility to model both soil-foundation and super-structure non-linearities is achieved only by performing complex and time-consuming finite-element analyses, which are rarely used in current practice, unless for very important structures, and which are hard to be used to perform parametric analyses.
It is believed that the proposed simple numerical tool represents a bridge between geotechnical and structural earthquake engineering, which can be helpful to better understand the interplay between non-linear soil-foundation and super-structure systems, and non-linear soil-structure interaction effects. Besides, it can perform very fast non-linear time-history analyses, so that it can be used for parametric analyses, and to aid the design and verification process.
The third part of the thesis concerns the application to seismic design. In the framework of a research project funded by the Italian Department of Civil Protection, a new iterative design procedure is developed, which takes into account non-linear soil-structure interaction effects in the displacement-based design. The key ingredient of this pseudo-static procedure is the linear equivalent visco-elastic characterization of the soil-foundation cyclic behaviour, which is achieved through the construction of curves of foundation rotational secant stiffness degradation and increase in damping as a function of foundation rotation. These curves are subsequently introduced in the Direct Displacement Based Design (DDBD), which is in turn based on an equivalent linear visco-elastic approach. An iterative procedure is implemented to take into account non-linear soil-structure interaction effects in this displacement based design method; it is denoted as DDBD+SSI, and it is based on an equivalent linear visco-elastic 1 dof oscillator (Fig. 2). Some design examples, referring to the bridge pier structural type, are illustrated and discussed, by comparing the proposed DDBD+SSI procedure with conventional force-based and displacement-based design. Design results are finally checked by performing non-linear time history analyses by means of the previously introduced macro-element based numerical tool.
Conventional non-dimensional parameters used to characterize dynamic elastic soil-structure interaction effects are discussed and preliminary considerations are made concerning non-dimensional parameters which could characterize non-linear SSI.
The final objective of the work has been to develop a simple, robust and accurately validated tool, intended to support the introduction of non-linear dynamic soil-structure interaction in the framework of performance-based seismic design and verification procedures.



1. Numerical model for dynamic soil-structure interaction analyses



2. Equivalent 1 dof oscillator used by the DDBD+SSI procedure

MATERIAL MODEL CALIBRATION BASED ON FULL-FIELD MEASUREMENTS AND INVERSE ANALYSIS, WITH APPLICATIONS TO CONCRETE DAMS AND ANISOTROPIC FREE-FOILS

Tomasz Garbowski

The formulation and solution of inverse problems have had an enormous increase in the last decades in many different fields, from medical imaging techniques to methods for locating oil in the earth's substructure (geophysical prospecting) and to ultrasonic non-destructive testing, just to name a few. With reference to engineering mechanics, the inverse problems approach has found fruitful applications in areas like heat transfer, interpretation of complex material behaviour, elastodynamics and many others.
Generally speaking, inverse problems are concerned with the determination of some input or of some characteristics of a mechanical system from some of the system output. This can also be rephrased, more concisely, by saying that inverse problems are problems where causes for a desired or an observed effect are to be determined. Especially in recent years, the increase in computing power and the ability to generate computational models for systems of growing complexity have made it possible to apply the techniques of inverse problems to many real-world contexts. An important class of inverse problems concerns the characterization of material properties and, more precisely, the evaluation of the parameters embedded in constitutive laws.
Standard methods for the determination of material parameters are based on the use of samples with a well defined standardised geometry and loading, such that particular conditions on the stress and strain field are satisfied in (at least a part of) the sample. In some situations, the application of standard methods is inconvenient or even impossible. Moreover, if the material is inhomogeneous or anisotropic, it is generally impossible to obtain homogeneity of stress and strain field in any part of the sample. In order to take the heterogeneity into account, mechanical tests based on non-standard experiments are now often coupled with full field measurement techniques (displacement, strain, temperature, etc) that better reflect the local behaviour of the material. These heterogeneous fields can be determined by means of widely use optical measuring techniques, such as shearography, laser speckle interferometry, and moiré. Recently, with the development of high resolution Charge Coupled Device (CCD) cameras the use of digital image correlation (DIC) method has increased considerably. DIC allows, in principle, to measure arbitrary complex (heterogeneous) displacement fields with relative simple instrumentation.
The identification of material properties exploiting whole-field displacement and strain measurements is a particularly active research area that has led to the development of various approaches, like: the finite element (FE) model updating technique, the constitutive equation gap method, the equilibrium gap method and the virtual fields method.
The finite element model updating technique is the most commonly used despite it entails large numbers of calculations. The main goal of the inverse analysis based on FE model updating method is to identify a set of unknown material parameters in a numerical model. These unknown parameters are determined iteratively by minimizing a cost function which expresses the discrepancy between the experimental and the computed response of the physical system under study, e.g. by comparing displacement fields, strain fields, resonant frequencies, etc. The "a priori" unknown material parameters in the FE model are iteratively updated in such a way that the computed displacement fields match the measured fields as closely as possible.
An alternative to the above described approach is the virtual fields method. This approach consists of minimizing the difference between the internal and external virtual work of the system. This method has two major advantages compared to the FE based inverse method: first, no time-consuming FE computations are required; second, it is not sensitive to the distribution of the loadings if suitable virtual fields are used. However, no specific rules for the choice of the virtual fields are available in cases of elasto-plasticity.
A different computational methodology for solving the inverse problem, which may avoid the above mentioned difficulties concerning computational burden and problematic choice of virtual fields, can be developed by recourse to soft computing, namely to Artificial Neural Networks (ANNs). A neural network is a "black box" that directly learns the internal relations of an unknown system. After a neural network learns the unknown relation from given examples, it can then predict, by "generalization", outputs for a different samples that are not included in the learning sample set. In this approach the FE model is used only in a "training" phase in order to generate the training samples. The main advantage of ANNs is that once they are trained later can be used on a small portable computer either "in situ" or in laboratory without any specific FE or optimization software.
In the Thesis the mixed computational-experimental methods based on FE model, inverse techniques and full-field measurements by DIC are investigated. The main goal is to develop a fast and robust identification procedure in order to estimate a set of unknown parameters in various numerical models. The unknown parameters are determined herein either by classical iterative minimization algorithm, such as Trust Region Algorithm (TRA) or/and by Artificial Neural Networks.
The developed and implemented identification procedures are applied on two different technological fields: identification of orthotropic elasto-plastic material models in free-foils based on biaxial cruciform laboratory tests and; identification of the material parameters and a state of stress in possibly deteriorated concrete dam based on flat-jack "in situ" diagnostic tests. In both examples the measurements of displacement fields are assumed to be provided by DIC system in "a priori" chosen correlation grid. The numerical models are used to simulate experiments and generate the pseudo-experimental data.
In both procedures crucial role (and innovative in the present context) is played by a mathematical techniques usually called "Proper Orthogonal Decomposition" or "Principal Component Analysis" apt to substantially reduce the computational efforts to be done in each practical applications and to confine them to a preliminary, "a priori" once-for-all phase of software generation.

STRUCTURAL ROBUSTNESS OF DETERIORATING SYSTEMS

Paola Limonta

Events of structural collapse have shown that the initial failure of a structural element may become the cause of the failure of other elements provoking a spread of the initial damage in the structure up to collapse, known as progressive collapse mechanism. In order to predict the possible occurrence of such a mechanism and to assess its proportions, it is necessary to study the behaviour of the structure as a whole.
In this context the concept of structural robustness has been introduced, in order to define the ability of the structure to withstand an initial damage with consequences not disproportioned to the cause of damage itself. Since 1968, after the Ronan Point partial collapse, tools suitable for the representation of progressive collapses and methods for the enhancement and the evaluation of structural robustness have been developed. The interest in this subject has been later renewed with the occurrence of the collapse of the Twin Towers in New York and of other public buildings caused by terrorist attacks. However, there is still no general agreement on the definition and on the measure of structural robustness. It is not clear how to estimate the initial damage, how to compare its proportions to those of the final consequences and how to define acceptable proportions between causes and effects. This difficulty is mainly due to the complexity of the system behaviour and to the several factors influencing it, and it is emphasized by the fact that it is evaluated with reference to events of exceptional nature.
The damage scenarios that can highlight the lack of structural robustness may be very different, from explosions to collisions, fires, natural phenomena and human errors. Among these, also damage processes due to environmental aggressiveness can be considered a triggering event, as some past events of structural collapses demonstrated. The causes of environmental aggressiveness considered in this Thesis are due to concrete carbonation and chloride ingress leading to steel reinforcement corrosion. They are ordinary phenomena which, in some cases, might cause disproportioned consequences, similarly to extreme events. Moreover, their slow growth in time allows not only to predict the possible effects of environmental damage, but also to detect their initial phases and, in case, to prevent them with appropriate maintenance plans and interventions.
The structural robustness of system under environmental damage is therefore investigated in this Thesis. To this aim, a numerical code suitable for static analysis of framed structures has been developed. In order to properly represent the propagation of damage, the cross-sections of the beam elements are described by means of quadrilateral iso-parametric elements, of steel or concrete, and, eventually, by a number of reinforcing steel bars. Geometrical and mechanical nonlinearities have been considered. Moreover, creep phenomena have been described because of the possible interactions with environmental damage processes. In particular, damage has been represented by means of three models of increasing complexity. The first consists in the removal of part of the cross-section; the second describes the progression of damage in time, by means of a series of environmental, climatic and material parameters; the third is able to represent in a more accurate way the aggressive agents diffusion process, taking into account the actual cross-section exposed surface.
The evolution of robustness in time in presence of environmental aggressiveness is first investigated from a deterministic point of view. Before evaluating the environmental damage effects on structural robustness, the effectiveness of the indices representing the initial damage has been considered. It has been found that global indices representing the overall amount of damage on the structure seem to be more representative of the proportions between causes and consequences rather than local indices which refer the structure response to the damage condition of one single point of the structure. Global indices allow also to appreciate the sensitivity of the structure to damage spatial distribution by comparing the shape of the curve representing the robustness index evolution referred to different damage scenarios. However, they present some limits, too, like not being defined in case of zero-length fractures or not considering the role of the damaged element.
An attempt to take into account the role of the damaged elements has been performed by weighting the initial damage index on the basis of the initial strain energy.
When environmental damage is considered, the evaluation of the damaged volume depends both on the elapsed time and on the shape of the cross-section. In fact, when different damage scenarios are considered, if the overall damaged length differs, the less safe scenario might not correspond with the less robust scenario nor resistance and robustness characteristics evolve in time in the same way. In particular, the representation of structural robustness evolution in time can be interesting for a maintenance intervention planning on the structure.
Besides, also the modelling of damage propagation on the cross-section influence the robustness estimate and evolution in time, since different cross-section shapes or different surfaces exposed to aggressive agents correspond to different reduction of the cross-section properties in time and therefore to different evolutions of structural robustness indices.
Moreover, the effects of environmental damage may cause changes in the failure mode of the structure, which represent a sudden variation of structure robustness. In this approach also the interactions between environmental damage effects and time-dependent behaviours have been considered.
The proposed deterministic approach has been finally extended in a probabilistic context to account for the uncertainty involved in the problem, in the numerical code this uncertainty have been considered by means of the Monte-Carlo method.
It has been shown that the uncertainties in the system response with respect to the damage index are influenced by the considered damage scenario and by the material behaviour, while they are less sensitive with respect to the rate of damage propagation. Nevertheless, all these aspects contribute in generating an increasing uncertainty in the evaluation of structural robustness in time.

RESIDUAL STRESSES AND THEIR INFLUENCE ON THE STRESS RELAXATION OF PRESTRESSING WIRES AND STRANDS MADE OF HIGH-STRENGTH DUPLEX STAINLESS-STEEL

Ha Manh

The objective of this study is to investigate the mechanical properties of the rather innovative duplex stainless steel, that has been recently proposed for R/C structures. The mechanical properties of the wires are studied experimentally and numerically. As a result of the cold-drawing process, the residual stresses strongly affect the mechanical properties of the wires. Hence the thesis is not only aimed to study the mechanical properties of the cold-drawn wires, but also to model the whole thermo-mechanical treatment.
Many aspects of the residual stresses are recalled and modeled with their effects on the mechanical response of the material (such as fracture toughness and micro-structural stability).
Numerical analyses are performed to simulate the residual stress-relief process via available software. The results show a good agreement with the tests, this being a demonstration of the validity of the proposed modeling technique and of the soundness of the experimental findings.

OPTIMIZATION OF MAINTENANCE PLANNING OF STRUCTURES IN AGGRESSIVE ENVIRONMENTS

Roberta Stucchi

For many centuries concrete structures were believed indestructible, but over time many evident effects of deterioration processes brought to light their weaknesses.
Due to them, non-scheduled and expensive emergency maintenance programs were often required in order to provide adequate serviceability and reliability. This results in a large amount of money spent in annual repair programmes to rehabilitate the most strategic or important structures.
Many investigations of the main causes of early damage in reinforced concrete structures were carried out over the last years, and designers became more focused to contrasting or reducing efficiently the main environmental and anthropic causes of damage, considering the whole service life. Uncertainties of the parameters related not only to the strength of materials, but also to loading factors, and time-dependent effects like creep, shrinkage and deterioration processes are considered within structural analysis. Based on the definition of structural response over time, the failure time, when the service limit states, or even the ultimate limit states, are no longer satisfied, may be detected.
In literature, several numerical programs able to define the best maintenance schedule and to evaluate the effects of the interventions are available. Nevertheless, these programs are all based on the data obtained by surveying campaigns on structures having similar characteristics. Of course, this process cannot be carried out in case of fragmentary or incomplete database, or of innovative or not ordinary structures.
In this work a general and systematic approach, capable of simulating the evolution of the structural behaviour over time is presented. This approach considers on one hand, the time-dependent effects and, on the other, the environmental conditions and the service loads applied to the structure. To this aim, MAINTENANCE, which is a specific tool for the assessment of structural serviceability and durability of reinforced concrete structures over the whole service life, is developed. This tool consists of three moduli. The first one provides a prediction of the structural behaviour, considering the time-dependent effects, the loading sequence and the deterioration processes induced by environmental conditions. This modulus also allows to assess the enhancement of serviceability and reliability of the structure after a repairing intervention. In the second modulus, the results obtained with the first one are synthesized into a performance index. Finally the third modulus identifies the maintenance policy which combines the minimum life-cycle costs with an effective management of the structure.
To capture both time-dependence and the uncertainties associated with the actual condition of the structure, which is a result of the deterioration processes combined with the outcome of the maintenance interventions, a Markovian model is chosen. The model requires the structure to be subdivided into different groups of components, each defined by a limited number of condition states. The current state is linked to the others by means of transition probabilities, which depend on the action undertaken on each group of structural components.
At the end of the evaluation carried out with MAINTENANCE, a set of different maintenance policies is obtained and sorted by increasing order of cost. The cost alone cannot be considered as a decisive parameter, as, in the cases studied, the better ranking policies were found to have similar costs. At this point, the best policy is therefore chosen by the decision maker, who will take into account further criteria which cannot be easily codified and implemented in the commercial tool. The final outcome of the procedure described is a Maintenance, Repair and Replacement interventions (MR&R) programme, associated to minimum life-cycle costs.