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PhD Yearbook | 2018

Chair:
Prof. Roberto Paolucci

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

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 for micro-systems), (b) structural systems (from constructions to bio-mechanical systems and micro-systems), (c) soils and (d) environment-structure interaction.
Deeply-rooted in the Civil Engineering, which is in itself highly inter-disciplinary, SSGE focuses also on environmental actions, either external (such as earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction (such as those caused by retained-earth thrust, landslides and water-table fluctuations). Due to their generality in materials and structural modeling, the methods developed within the domain of SSGE can be of great importance also in other technical-scientific fields, whenever understanding and controlling mechanical aspects is necessary to guarantee design reliability and structural safety, as well as serviceability and durability. Many are the themes arising in connection to 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 forget the topics shared with some branches of the Industrial Engineering.
Within this framework, the main goal of our Graduate School is to promote the advancement of knowledge especially in the fields of: (a) innovation in materials and structures; (b) building safety under highly-variable actions; (c) stability of soils and surface/buried structures.
We pursue this goal by offering our PhD Candidates an advanced, research-oriented background, based on both the pivotal role of Structural Engineering and the multi-disciplinary nature of Seismic and Geotechnical Engineering.

Contents of the Doctoral Program

Attainment of a PhD in Structural, Seismic and Geotechnical Engineering is conditional to: minimum three full-time years' study and research activities; the development of a PhD thesis; the fulfillment of the minimum requirements provided in terms of PhD level courses.
Candidates are offered a variety of advanced courses on different topics, including mechanics of soils, materials and structures; computational and experimental methods; structural dynamics and earthquake engineering.
The study plan includes courses and seminars given by scientists, experts and researchers active either at the Politecnico di Milano or in other Italian and foreign Universities, research institutions and high-tech companies.
During their studies, PhD Candidates should develop their own original research work, coherent with the main disciplines dealt with in the Doctoral program, which will be detailed in the PhD thesis.
The thesis should clearly state the goals of the research work, explaining the relation with the state-of-the-art, the methods and the original results obtained.
The PhD research is developed under the guidance of a supervisor.
In order to widen and improve their research experience, PhD Candidates are strongly encouraged to spend a period abroad in one of the many Universities and research centers related to the Politecnico di Milano.
At the same time, the PhD School supports foreign scholars to give short courses and seminars in Milan, so that our PhD Candidates can constantly benefit from the opportunity to interact with the international scientific community.

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INTEGRATED STRUCTURAL MODELLING AND EXPERIMENTAL OBSERVATIONS IN HISTORIC MASONRY CONSTRUCTIONS

Grigor Angjeliu - Supervisor: Prof. Dario Coronelli
Co-Supervisor: Prof. Giuliana Cardani

Within the scope of restoration projects, structural models are used to better understand the structural performance of historical masonry buildings, as well as to design new restoration interventions.
The simulation of the structural response in historical buildings, from a mechanical point of view, is a complex problem. It includes complex geometry of structural members, their connections, mechanical properties resulting from the varying texture of masonry and additionally complicated by anisotropy due to present damage. Ageing, long history of construction, loads and interventions, may be only partially described or even unknown. Furthermore, the determination of material properties entails several uncertainties and presents practical testing problems. Under these conditions, visual observations of cracks, observation of the masonry texture, measurements of complex geometry, measurement of the axial force in the iron ties or the state of stress in masonry, are important evidence for approximating the real mechanical state. Structural modelling must take these evidence into consideration, here called *experimental observation*.
A bi-directional connection between structural models and experimental observations is needed. Here, the choice is made to gather the most information possible in order to setup a model and to calibrate this in relation to its performance in reproducing the phenomena observed *in-situ*.
The first part of the thesis is focused on understanding and modelling the three-dimensional geometrical complexity of historical masonry buildings. An innovative procedure was created to develop a geometrical model with a close relation to the real building structure. The procedure includes: the acquisition of geometry (photogrammetric measurements and observations), data elaboration and use of parametric procedures to generate complex parts of the system (i.e. nodal zones, vaults). The data elaboration considers shape identification algorithms implemented in Matlab, while the parametric model is implemented in IronPython programming. The model is finalised for use in a three-dimensional with solid elements, numerical finite element analysis of the structural response. A discussion on the approximation is developed in two case studies (the Cathedral of Milan and the Church of San Basssiano in Pizzighettone). The developed procedure, reduces the cost of developing complex three-dimensional solid structural models.
The second part of the thesis focuses on the development of detailed continuum and discrete numerical models, starting from the previously created geometric models. The importance of developing complex numerical models on a small and large scale is demonstrated in different case studies, by the type of phenomena and structural response that can be predicted.
a) small scale model; the case study of the quadripartite vaults in the Cathedral of Milan is adopted. Starting from the developed parametric modelling procedure different discrete and continuum models are developed. The models include the tas-de-charge, arch and rib (considered through many voussoir-s with contact among them), web, rubble-fill, as well as the contact interfaces between the considered parts. In difference to the state of the art, the discrete models include interfaces, in critical locations where damage was observed physically. Complex damage phenomena (all observed in-situ) such as the detachment of the rib from the web or sliding of the rib stone units, were predicted through the models with preassigned interfaces at critical locations, where damage is observed experimentally.
b) large scale model; the case of the nave of Milan Cathedral is adopted. Two large scale detailed models were developed, one considering a single bay and the other considering multiple bays of the nave. It was possible to evaluate the structural evolution over a period of time, predict and interpret the measurements of the axial force in the iron ties, providing interpretations about the tie failures in different periods, where prediction is not possible with simplified models.
The last part of the dissertation considers limit analysis solutions for historical masonry structures, providing synthetic results, to practical – engineering problems. The innovative aspect relies on the integration of experimental observations in analytical solutions. The approach was developed through several case studies. It is based on the correlation of in-situ measurement (e.g. out-of-plumb, rotation, settlement) and observation that includes elements failure (iron ties), experimental force measurement on the iron ties and the onset of damage in masonry elements (described by cracks and decay) with the created analytical models. In the proposed method, the unknown quantities in the structural system (e.g. the distribution of forces), are obtained through observations and measurements in the system. The selected solution within the infinite possible solutions, compatible with the observed damage and deformation of the system, gives a better approximation of the actual behaviour of the system.
The models developed following the procedure here proposed give results that agree with the experimentally observed response of the structural systems under study. This shows their validity for the interpretation of observed structural events and monitoring system data, as well as in the study of structural intervention in restoration projects.

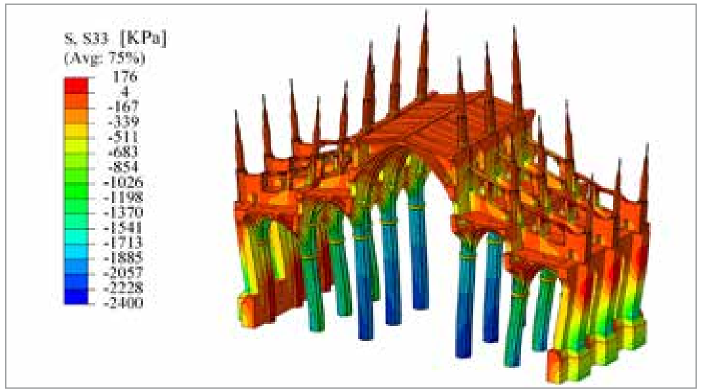

Fig. 1 - Plot of the vertical component of the stress due to self-weight

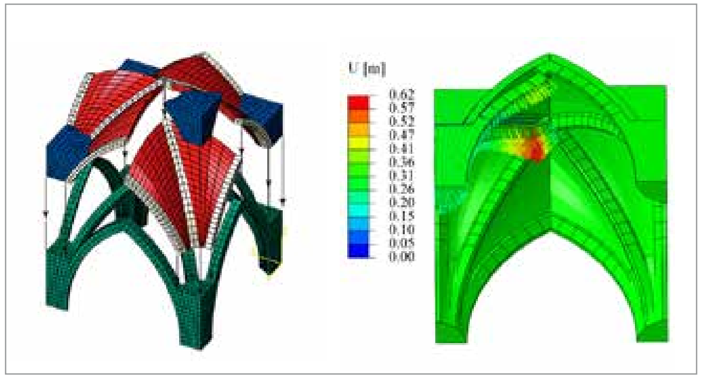

Fig. 2 Structural model of the ribbed masonry vault. a) Finite element mesh, b) Simulation of the collapse mechanism

OPTIMAL DESIGN OF SENSOR NETWORKS FOR STRUCTURAL HEALTH MONITORING

Giovanni Capellari - Supervisor: Prof. Stefano Mariani
Co-Supervisor: Prof. Eleni Chatzi

The objective of the work presented in this thesis is the development of techniques for the optimal design of sensor networks for Structural Health Monitoring (SHM). Two methods are here proposed, a deterministic and a stochastic one.
In the first one, the uncertainties associated with both the measurements and the mechanical parameters to be estimated (e.g. stiffness, Young's modulus or damage index) are disregarded. The optimal sensor placement is obtained by maximizing the sensitivity of the structural response with respect to a variation of the mechanical properties to be estimated. In order to guarantee a low computational cost, even for high numbers of problem unknowns (number of sensors), a topology optimization scheme is adopted. Moreover, in order to account for the different length-scales of the problem, i.e., the dimensions of the structure, of the damaged zones and of the sensor boards, a multi-scale optimization approach is introduced. The procedure allows to both reduce the computational cost of the optimization problem and appropriately tune the spatial resolution of the solution. The strategy is applied both to a benchmark problem, a clamped square plate, and to a section of stiffened fuselage.
The second method here proposed is based on Bayesian experimental design: the optimal sensor placement is obtained by maximizing the expected Shannon information gain between the prior and the posterior probability distributions of the parameters to be estimated. In order to numerically solve the optimization problem, the unbearable computational cost of the employed Monte Carlo estimator is greatly reduced by exploiting surrogate modeling techniques based on Polynomial Chaos Expansion (PCE), which allow to efficiently reproduce the input-output relations of the physics-based models. Two surrogate modeling strategies are introduced and compared: these are based either on the definition of a joint input variable, which takes into account both the parameters and the design variable, or on the combination of model order reduction methods, i.e., Principal Component Analysis (PCA), and PCE. In order to handle the noisy objective function, the adoption of a stochastic optimization method, namely the Covariance Matrix Adaptation Evolutionary Strategy, is introduced. Since the presented framework allows to take into account several experimental settings, i.e., sensor spatial configuration, number of sensors and measurement noise, a comprehensive method to optimally design the SHM sensor network is proposed. Moreover, different sensor network designs can be compared, taking into account both their cost and effectiveness, through a cost-benefit optimization approach, by adopting a Pareto frontier

Fig. 1 - Pirelli tower: case study considered for the optimal design of the structural health monitoring sensor network.

multi-objective optimization.
The procedure is applied to the benchmark problem already considered for the deterministic approach, and on a large-scale numerical application, i.e. the Pirelli tower in Milan (see Figures 1, 2, 3).
Since the capability of any monitoring system in estimating the mechanical parameters can be prevented if the parameters result to be practically non-identifiable, the use of information theory based indices is proposed in order to measure the occurrence of two sources of practical non-identifiability: the compensation of the effects of the parameters on the measurements is quantified through the conditional mutual information; the lack of sensitivity of the measured quantities with respect to each parameter is measured through the mutual information. The effectiveness of these indices is validated on a non-linear structural problem, i.e., an 8-storey shear-type building.

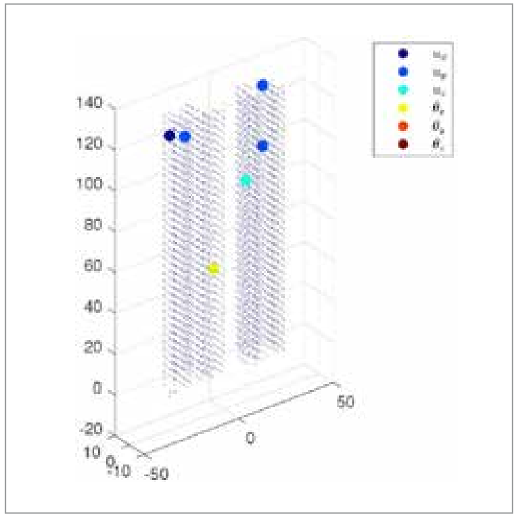

Fig. 2 - Pirelli tower: optimal sensor placement obtained through the maximization of the expected Shannon information gain

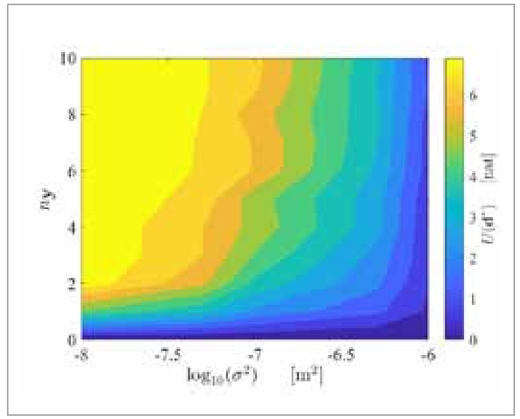

Fig. 3 - Multi-objective optimization of the expected Shannon information gain in terms of both the position, type and number of sensors.

VIBRATION CONTROL VIA PERIODIC STRUCTURES FROM MICRO- TO MACRO-SCALE

Luca D'Alessandro

Supervisors: Prof. Alberto Corigliano, Prof. Raffele Ardito and Dr. Luca Daniel

The study of wave propagation along spatially periodic structures is of great interest in solid state physics: one of the most interesting properties of these structures is the formation of bandgaps, i.e. portions of the frequency response for which an incident wave cannot propagate through the structure.
This idea is used in several applications in the electromagnetic domain, one example is the optic fiber, and more recently large interest has been devoted to spatially periodic mechanical structures, named phononic crystals.

Depending on dimensions and materials of the periodic structure, applications for mechanical meta-materials range from earthquake protection (*seismic metamaterials*) to noise isolation and thermal properties control.

In all these applications, is undeniable that bandgap width is a key factor to boost performances and robustness, wider bandgap means stronger attenuation around gap central frequency. Another important aspect is the dimension of the unit cell of the periodic structure, which should be comparable to the available space in each field of application.

In this thesis periodic structures are studied for vibrations and mechanical wave propagation control from micro to macro-scale engineering problems.
Focus is given to theoretical (both analytical and numerical) and experimental study of the periodic structure properties, with particular attention to applications, to shorten the distance between the theoretical study of such structures and the actual implementation in practical engineering problems.

For this purpose, several studies are conducted: wave propagation control in micro-sensors, mechanical tunable filters and low frequency ultra-wide 3D mechanical filters with reference to ground-borne vibration reduction in civil engineering problems.

A brand new shape optimization algorithm implementation based on Bidirectional Evolutionary Structural Optimization is developed, implemented and numerically tested on a micro-sensor application, showing to be faster in the optimization process than other proposals in the literature.

Three-dimensional periodic structures endowed with ultra-wide complete bandgaps are designed and experimentally tested, among which there is the most performing one in the literature.
The design strategy is described and a brand new simple analytical model is proposed, which is able to predict the 3D dynamical behaviour of these structures with a 1D spring-mass chain.
The good points of these structures are the ultra-wide range of isolation in the frequency spectrum and the low dimension of the unit cell, which is dozens lower than the wavelength of the propagating vibration, enabling the practical use of such structures in actual problems.

Combination of auxetic properties and frequency isolation is studied, leading to the design of a 3D meta-material with tuning filtering properties, which is numerically, analytically and experimentally studied.

The results described in this thesis are collected in several conference papers, 4 international publications and 2 patents.

FORWARD PHYSICS-BASED ANALYSIS OF "SOURCE-TO-SITE" SEISMIC SCENARIOS FOR STRONG GROUND MOTION PREDICTION AND SEISMIC VULNERABILITY ASSESSMENT OF CRITICAL STRUCTURES

Filippo Gatti

Supervisors: Prof. D. Clouteau (Laboratoire MSSMat UMR CNRS 8579, CentraleSupélec); Prof. R. Paolucci (DICA, Politecnico di Milano);
Prof. F. Lopez-Caballero (Laboratoire MSSMat UMR CNRS 8579, CentraleSupélec)

The French national project SINAPS@ (Earthquake and Nuclear Facilities : Ensuring Safety and Sustaining), which entirely financed my PhD thesis (https://tel.archives-ouvertes.fr/tel-01626230), was conceived to gather the information coming from the earthquake engineering and the seismology to integrate them into an omni-comprehensive computational framework. The intent is to improve common design practices of critical structures (i.e. nuclear power plants) and revise the existent ones, with an innovative physics-based and source-to-structure slant. To this end, the chosen applicative case is the seismic response of the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP), during the 2007 Niigata-Ken Chūetsu-Oki (NCO). The latter is a well documented seismic scenario, suitable for deep investigations on the near-field conditions, non-linear site-effects and structural analysis. Moreover, the site has been object of a previous numerical benchmark, which highlighted some critical aspects of the site and structural response.

In this work, I have explicitly focused on some crucial aspects of the physics-based modelling of the NCO earthquake scenario. Inspired by the proposals of SINAPS@, the forging idea of the PhD project was to analyze the different aspects of the problem, from a holistic point of view, featured by an uncertainty quantification. Owing to the multidisciplinarity of the modelling problem, an innovative hybrid approach was adopted, mixing high-fidelity physics-based simulation and machine-learning techniques applied to big databases.

The earthquake-induced ground shaking scenario was first investigated and understood by analyzing the available seismic record database. To this end, Chapter 2 present an extensive review of the consistent (yet hollow) piece of information available on the site. A complete seismic site-response classification was performed, to pave the way to complex physics-based analyses, helping in understanding the phenomenon and constrain the numerical model. The analysis of the seismic records highlighted the impulsive nature of the wave-motion along with the non-linear behaviour of shallow soil deposits. The second major axe of my thesis is the prediction of realistic yet synthetic broad-band time-histories, either (1) by pushing to the limit the accuracy of the deterministic computational models (i.e. ~ 7 Hz), either (2) by coupling them with meta-modelling predictions, such as the Artificial Neural Networks. The first strategy is intrinsically related to the appropriateness of the earthquake rupture and of the 3D geological models and rheology. Therefore, given the multifaceted nature of the earthquake phenomenon, the construction of realistic seismic scenarios was performed by exploiting different computational tools. I participated into the construction of a HPC (High-Performance Computing) multi-tool platform, whose main core is represented by a 3D Spectral Element code to solve the wave-propagation problem in viscous non-linear solid and fluid materials on massively parallel supercomputers. The code is featured by a highly scalable random field generator to simulate Earth's crust heterogeneity, along with a high-performance 27-tree based meshing tool to produce numerical model representing Earth's chunks, including topography and bathymetry.

In a common context of lack of inherent data, verification and validation against observations are the principal means by which the predictive capability of ground motion simulation methods and their implementation was assessed (Chapter 3). The study on the effect of heterogeneous and non-linear soil deposits on the simulated broad-band ground motion coherency at the surface was assessed.

In the following, the physics-based simulation of the KKNPP seismic response during the Niigata-Ken Chūetsu-Oki earthquake was tackled. The numerical model was constructed starting from a simple version, progressively updated. The main uncertainty I investigated was the effect of the geology on the simulated regional wave-field. The simulation of two small aftershocks steered the calibration of a hybrid geological profile composed of (1) a layered 1D geological structure, suitable to reproduce the low-frequency (0.0-0.5 Hz) regional wave-field and of (2) a refined 3D folding model, capable to depict the spatial variability at KKNPP (up to 7.0 Hz). The analysis unveiled the reason behind the great ground motion incoherence recorded within relative short distances at the nuclear site: the syncline-anticline structure lying below the site caused a wave-motion drift towards Unit 1, where higher amplitude were effectively noticed. This implies the need for an accurate investigation of the deep geological profiles (i.e. up to □ 5.0 km of depth) when the critical and spatially extended structures are designed, other than the geomechanical characterization of shallower (i.e. up to ~ 500 m of depth) soil deposits, responsible of non-linear site-effects. However, to study the transient dynamics of rigid structures (such as the nuclear reactor buildings, conceived for safety issues and embedded in the first meters of soil down depth) requires broad-band synthetic earthquake seismograms, to be used in a design stage. However, the limited spatial discretization of a typical computational grid that a common supercomputer can handle nowadays limits the resolution of of the simulated 3D wave motion, accurate to maximum frequencies at around 5-10 Hz. Therefore, Chapter 4 describes a new procedure (ANN2BB) for the hybrid generation of broad-band synthetic time-histories. This strategy bypass the hinder of burdensome computations, slightly deviating from the trending way of improving the earthquake prediction at larger frequency bands by simply constructing more complicated and fancy models. However, ANN2BB bares upon physics-based numerical simulations, by coupling the latter with the outcome (i.e. short-period pseudo-spectral ordinates) of Artificial Neural Networks, opportunely trained on heterogeneous seismic databases. This hybrid approach gravitates around the need for realistic time-histories, whose response spectrum is compatible to the recorded observations. ANN2BB was applied to some recent earthquakes, with interesting results in terms of site-specific estimated time-histories. It represents a very appealing alternative to fully deterministic analyses, whenever the physical mechanism lying behind the observed records are not easy to be modelled at a certain scale. With the respect to traditional hybrid approaches (based on empirical or semi-empirical methods), ANN2BB should be able to preserve the ground motion coherency observed at low-frequency. ANN2BB represents a smart meta-modelling technique to effectively cope with the lack of data, of suitable models, of computational resources and, least but last, of a deeper understanding of the earthquake phenomenon.

This document can be seen as a seminal work, to be integrated in the very near future with some fringe aspects, such as the modelling of the dynamic rupture of large fault discontinuities, the full coupling between regional-scale wave-propagation numerical models and site-scale structural analysis and the inclusion of complex rheological models for the Earth's crust and soil deposits. All those aspects are intended to be integrated with sophisticated deep-learning techniques, to increase the overall prediction on complex earthquake scenarios, aiming at refining seismic vulnerability and risk assessment in large urban areas and for strategic structures.

EFFECTS OF THE SPATIAL VARIATION OF THE SEISMIC GROUND MOTION IN NEAR FIELD CONDITIONS ON LONG BRIDGE STRUCTURES

Cristian Gianni - Supervisor: Prof. Lorenza Petrini

This work follows the line of research in earthquake engineering that deals with the response of lifeline structures, namely bridges, to a spatially variable ground motion. Seismic structural analysis and design practice is traditionally based on the assumption that structures experience the same ground shaking at all the supports. This means that the amplitude, phase and frequency content of the motion are identical at all the points of contact between the structure and the ground. However, the characteristics of the motion recorded at the supports may become significantly different as the distance between these points increases and/ or the site conditions change. This phenomenon is known as *spatial variability of the earthquake ground motion (SVEGM)* and its detrimental effects on the response of structures, namely lifelines, is nowadays well recognized, contributing to the damage or collapse of several structures during past and recent earthquakes. In fact, SVEGM may cause unpredictable seismic demand patterns in the structural elements with respect to strength, ductility or displacements. Recently, the data recorded and collected in dense instrumented seismic arrays worldwide (SMART1 in Taiwan, Chiba in Tokyo and USGS-Parkfield in California amongst the others) gave new impulse to the research, which gradually has extended its efforts to challenging applications, i.e. the development of analytical tools for the generation of spatially variable ground motions and dealing with structural models of increasing complexity. Despite the topic of the spatial variation of the earthquake motion and its effects on the structural response has stimulated the interest of a wide number of researchers for over four decades, owing to the multi-parametric nature of the problem, common conclusions have not been reached yet and several questions remain unanswered. This research aims to provide a further contribution about the topic, extending the range of the case studies investigating very long structures, with length up to 1000 m. In particular, a parametric study on the nonlinear response of a series of long bridge structures subjected to spatially variable ground motions is performed emphasising the influence of the following aspects:

- Medium- and long-length bridges;
- Irregular geometries in elevation;
- The presence of bearings devices in the structural modelling;
- The bay length;
- The ductility level of piers;
- The pier type.

The structures are excited by three sets of spatially variable ground motions derived from real records of the Parkfield 2004 and San Simeon 2003 earthquakes available from the UPSAR and the Turkey Flat Valley arrays. The structural responses to the incoherent and to the fully coherent excitation are compared with the aim to contribute to the identification of the cases in which the uniform excitation assumption becomes unsafe. Results show that multiple-support excitation may increase the seismic demand in terms of accelerations, displacements, shear force and bending moment in the piers of irregular bridges on average up to 50% with respect to the uniform excitation case. Finally, the effectiveness of the simplified approaches of the Italian design code NTC08 and Eurocode 8-2 in the prediction of the response of the selected bridges under multiple-support excitation is assessed comparing the results obtained by the application of their provisions with to those of the nonlinear time history analyses.

NON-LINEAR EFFECTS ON THE SEISMIC RESPONSE OF BUILDINGS WITH FOUNDATION-STRUCTURE INTERACTION

Giovanna Pianese - Supervisor: Prof. Roberto Paolucci

Co-Supervisor: Prof. Stefano Parolai; Dott. Antònio A. Correia

Dynamic soil–structure interaction (SSI) involves the coupling of structure, foundation, and soil that, especially during an earthquake excitation, may reach a substantial level of complexity, particularly when non-linear effects come into play. Since SSI requires evaluating the collective response of these systems to a specified ground motion, boundary conditions should be properly introduced to model, on one side, the unbounded domain of analyses and, on the other side, the interfaces between the different coupled systems. Such complexity is further increased by the different scales involved in the SSI model that may range from the tens or hundreds of meters to model the soil, to the fractions of meters to model the structural and foundation details. For these reasons, modelling the dynamic SSI effects, especially in presence of non-linearity, is still a challenging research problem, involving several modelling simplifications.

Within the vast framework of dynamic SSI effects, this thesis aims at shading further light on two subjects which have provided significant progress in the last few years, but still deserve considerable attention, namely:

- the identification of non-linear structural response of instrumented buildings in presence of SSI;
- the numerical modelling of the non-linear seismic response of foundations and its interaction with the super-structure through an improved 3D macro-element model.

In the first part of the thesis, a novel approach, which takes advantage of the deconvolution interferometery and S-Transform time-frequency analysis, has been proposed to detect the non-linear seismic behavior of structure in presence of SSI effects, which, if not properly accounted for, may lead to improper evaluation of the dynamic properties of the building and misinterpretation of their changes during an earthquake. The main advantage of the proposed method is that it allows to follow step by step the evolution of dynamic parameters, the variation of which, in case they occur, are reasonably associated with the degradation of the building stiffness. Such variations are considered as a global indicator of the occurrence of damage. Four case studies of instrumented buildings have been treated to investigate the capability of the proposed approach to detect the occurrence of damage during and after a seismic event. Buildings slightly and severely damaged have been considered. The results of such applications have lead to an estimation of threshold frequency change associated to non-structural and structural damage. The definition of such thresholds depends only on the decrease (in %) of the frequency, and does not depend on its absolute value, which may not be accurately reproduced by the simple formula based on the shear beam model. The important aspect of such indications is related to their practical use to detect damage when it occurs, and issue an early warning during or soon after earthquakes, and before costly physical inspection. The final objective of this first part is to provide a simple tool that is able to give information about the status of a building, based only on data-earthquake processing.

The second part of the work concerns the numerical modelling of the non-linear seismic response of foundations and its interaction with the super-structure. An improved 3D macro-element model, proposed by Correia (2013), has been presented: it builds upon the well-consolidated concepts and formulations of the previous models. Nevertheless, it incorporates some major improvements, namely addressing inconsistencies regarding the formulation of the participating mechanisms such as the soil-footing geometric (uplift) and material (soil plasticity) non-linearities. Moreover, this macro-element introduces a significantly enhanced uplift model, based on a non-linear elastic-uplift response which also considers some degradation of the contact at the soil/footing interface due to irrecoverable changes in its geometry. An improved bounding surface plasticity model is also adopted in order to reproduce a more general and realistic material non-linear behaviour, which correctly takes into account the simultaneous elastic-uplift and plastic nonlinear responses. The initial formulation of the new macro-element has been improved in parallel to an extensive validation phase against results of an international experimental dataset that includes both large-scale and reduce-scale tests. The selected dataset varies in model size, testing equipment, superstructure properties, footing shape, supporting soil environment and loading protocol. Both uplifting-dominating response and plastic settlement-dominated response have been investigated by using tests with different initial safety factor for vertical load, ranging from 4 to 30. Ground motion inputs include both cyclic loading of varying amplitude and real or artificial earthquake motions. In all experiments, the foundation lies on the sand with a relative density that varies from 40 % to 90%. The purpose of this validation is twofold: - taking advantage of well documented and available international experimental dataset, to propose an update non-linear macro-element able to reproduce with satisfactory accuracy the observed response of soil-foundation-structure system under dynamic loading, with emphasis of non-linear behaviour of soil-foundation interface; - to quantify and constrain the variability of the macro-element parameters to increase its robustness and its potential use for application to real cases.

The remarkable agreement achieved between the numerical results and observed response gives important indication of the robustness and accuracy of the macro-element model. The good, and in some case excellent, agreement between simulated and observed response of foundation subjected to different shaking inputs demonstrates that the numerical model is able to qualitatively and quantitatively reproduce the experimental behaviour, also when the dynamic non-linear soil-foundation behaviour play a dominant role. The prediction of foundation displacements fits very well the experimental results.

The main achievement of the model validations has been to define a default set of macro-element parameters values that ensures an overall good performance of the model. The practical indications regarding the selection of the parameters are also provided related to: (i) geometric and elastic parameters; (ii) strength parameters; (iii) model specific parameters. The limited number of model specific parameters to be defined is a key aspect that may favour the practical use of this model either for application to real cases or for parametric studies.

Since the 3D macro-element is implemented in SeismoStruct finite element code, this model can be mainly intended as an appropriate tool to allow effective soil-structure interaction analysis of structures with most interesting applications in earthquake engineering. To this regard, an ideal three dimensional RC frame structure on shallow foundation is considered, and both non-linear responses of the superstructure and of the foundation are accounted for. The results of the numerical dynamic non-linear analyses of an ideal RC structure subjected to real earthquake motions have pointed out that the tool is appropriate to investigate the role of dynamic soil-structure interaction in the seismic response of the structure and foundation system, with low computational cost.

The main objective of the second part is to contribute to improve the accuracy of numerical tools, calibrated by the increasing number of carefully controlled experimental results, and to make feasible the practical application of dynamic non-linear foundation concepts to most interesting applications in earthquake engineering.

COMPUTATIONAL MICROMECHANICAL ANALYSIS OF METAL CERAMIC COMPOSITES

Pandi Pitchai - Supervisors: Prof. Gabriella Bolzon and Prof. Michal Basista

Low chemical affinity and complex production process can prevent an adequate coupling between the components of metal ceramic composites. Thus, imperfect geometries and interfaces can compromise the overall performances of these advanced materials. The mechanical problem has been analyzed in the extreme conditions of perfect adhesion and pure friction between the matrix and the reinforcement of composites with periodic microstructures evidencing the different load transfer mechanisms. The results of this study performed in small strain regime evidence the sensitiveness to poor friction in a situation where the overall response of the composite appears to be linear. In fact, the nonlinearity detected in the simulation will be hardly evidenced by experiments and is prone to be confused with an initial settlement of the investigated material sample. Localized damage and debonding processes induced by the growth and coalescence of micro-voids in the metal phase have been also analyzed by the widely employed Gurson Tvergaard Needleman (GTN) damage plasticity model. The study was carried out in order to distinguish the effect of the material microstructure on the overall material response. The results of this investigation show that the macroscopic response of the analyzed MMCs is almost insensitive to volume fraction. The fibre arrangement mainly influences the apparent ductility of the material induced by plastic strain localization. The study considered both periodic and quasi-periodic fibre arrangement in the unit cell. The considered GTN model involves nine material constants. The value of each parameter depends on the production process of the composite. Therefore, no direct approach allows to determine the actual metal properties. A sensitivity study has been further performed to evidence the local mechanical characteristics, which can be potentially determined by indirect calibration procedures. An approximate analytical model of Proper Orthogonal Decomposition (POD) coupled with interpolation by Radial Basis Functions (RBFs) has been developed for its possible use in inverse analysis. The efficacy of this approach has been verified with some combination of GTN material parameters, to predict the material response including the plastic deformation with reasonable accuracy in short computational time. Finally, the role of interfaces on the failure mechanism of a real composite has been investigated. The analyzed problem has been considered under micromechanical bending of a material sample with perfect bonding condition. It is found that the real failure mode of the sample cannot be captured in this hypothesis.

Keywords : metal ceramic composites; micromechanical models; frictional interfaces; damage; debonding; POD-RBF approximations; metal failure; localized damage.

AN EXPERIMENTALLY DRIVEN COMPUTATIONAL ANALYSIS OF THIN LAMINATES

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The versatile application of thin metal laminates is spreading in different technological fields, for the production of flexible electronics, nano or micro-devices and beverages packaging. The actual material coupling is usually designed in order to meet different functional requirements, including the bearing of mechanical actions. Specific features of these composites are the small thickness of the layers, which may behave differently from the corresponding bulk materials. Hence, current research topic concerns material systems made of the coupling of thin metal foils, polymer plies and, possibly, with paperboard which, the role of each layer is substantial to enhance the functionality of above systems. Therefore, according to complexity of considered materials, three investigations were studied concerning the introduced applications: micro-mechanical behavior of freestanding aluminum foil (Al foil) and simulation of crack propagation, mechanical behavior of thin laminated structure made of Al/polymer coupling and an inverse analysis procedure for the constitutive parameters identification of a heterogeneous material (including paperboard composite and Al laminate). The numerical models were performed in small linear elastic strain and large plastic strain regime. Al and polymer were considered as an isotropic material, and their behavior was described by isotropic linear elasticity and Huber-Hencky-Mises plasticity model. The homogenized material response of the paperboard composite has been expressed by the orthotropic linear elasticity and Hill's plasticity model.
The selected Al foil has 9 micron thickness. Its mechanical response was evaluated on the basis of uniaxial tensile tests performed on plain and initially notched material samples. Displacements were measured during the experiment using three-dimensional digital image correlation (3D DIC) technique. Different numerical models were developed to study the failure mode of Al foil and its mechanical behavior using plane stress, shell and membrane elements. The problem exhibited high sensitivity to the modeling details. Simulations based on shell elements reproduced the wrinkling phenomena which also occurred in the experimental test (figure 1: a, b) but could not capture the observed failure mode. On the other hand, membrane elements simulated a realistic failure mode but without any wrinkles. Crack propagation was simulated introducing an interface layer characterized by a bilinear traction-separation law and discretized by cohesive elements. The interface properties calibrated based on the engineering stress-strain curve of plain sample could capture the response of both center and side cracked Al foils accurately.
The adhesion properties of the interfaces can usually be characterized only indirectly. The effect of different interface and material properties on the overall response and on the failure mode of Al/polymer laminate has been investigated numerically in an extensive parametric study. The influencing parameters consist of thickness and Young's modulus of the polymer layer, different interfacial properties and a type of imperfection (Al and polymer with the wavy-shape surface).
The necking phenomena due to thinning of the Al foil was defined as the overall load carrying capacity of the Al laminate which is relevant to Al constitutive properties. Despite significant effect of polymer thickness on the nominal stress-strain curve of the laminate, its behavior is unaffected by the change in polymer Young's modulus. The interface characteristics influenced mainly the softening regime.
The mechanical response of paperboard laminates, which are used in beverage packaging, has been finally investigated. In this case, realistic biaxial stress states were induced by inflation test. 3D DIC returned the whole displacements field in the heterogeneous sample. These measurements were exploited to characterize the materials by inverse analysis and utilizing trust-region-reflective algorithm. The numerical model results based on the identified material properties showed excellent agreement with the experimental output (figure 2: a, b). In the end, a sensitivity analysis performed on the anisotropic behavior of the paperboard composite emphasized that the anisotropic behavior become more distinguishable by embedding a laminate inclusion or by making a hole in the paperboard composite.

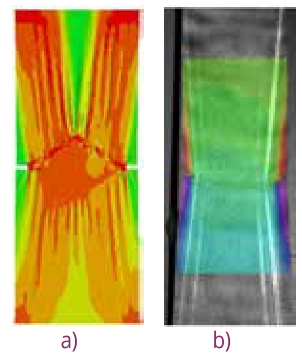

Fig. 1 - Appearance of wrinkles on the Al surface under uniaxial tensile test, a) numerical model and b) experimental test.

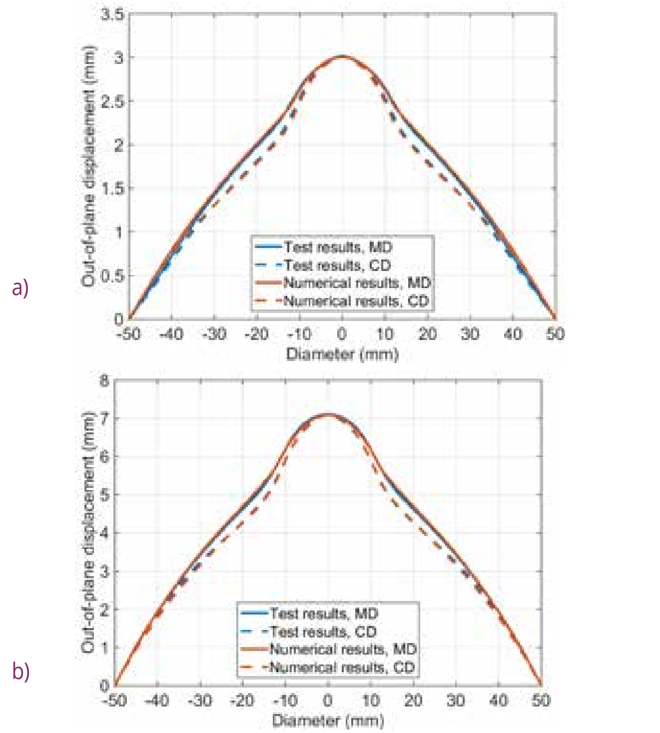

Fig. 2 - Comparison of out-of-plane displacement between experimental results and numerical results using optimized parameters at (a) 100 mbar, (b) 500 mbar.

NON–LINEAR SOIL–STRUCTURE INTERACTION FOR 3D EMBEDDED SYSTEMS UNDER SEISMIC EXCITATION

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In everyday engineering practice, seismic design of structures and infrastructures is usually performed by assuming a ductile response of the superstructure, while the foundation and the surrounding soil are supposed to be not subjected to any damage: in structural analyses, they are thus assumed as linear (or equivalently linear) elastic. The ductility control for the prevention of collapse mechanisms under a design-level earthquake is ensured according to the principles of the classical capacity-based design, which identifies the key regions of expected inelastic deformation within the structure and prevents failure modes elsewhere in the system. Such requirements, leading to conservative design, can be ascribed to time and costs related to post-earthquake safety evaluation of foundations and to the lack of well-established and calibrated methods to evaluate the plastic behaviour of both soil and foundations under strong earthquakes. Nevertheless, the unavoidable occurrence of non-linearities in the soil and at soil-foundation interface has been highlighted by recent earthquake ground motions characterized by large spectral and ground accelerations, especially in near fault areas. In addition, recent researches on seismic Soil-Structure Interaction (SSI) have emphasized the role of the soil compliance and of non-linearities in the soil-foundation system on the seismic response of structures. In this respect, the more recent performance-based design philosophy enables the characterization of the desired seismic performance of the structural system under a specified level of earthquake ground motion without any prescribed method, thus allowing, in principle, to account for all sources of non-linearities above and below the ground level and to ensure a cost-effective seismic design. Within the context of the performance-based design, non-linear SSI effects on the seismic response of structural systems need further assessment and insights and proper consideration in numerical approaches and methods with respect to the present state-of-the-art.
Although SSI represents one of the most classical topics in earthquake engineering analyses, research issues about non-linear effects have been mainly investigated only in last three decades, due to emphasis on limit state design and to the support of advancements in computing power. In addition, in SSI studies limited attention has been devoted to the seismic behaviour of embedded foundations, which are usually designed on the basis of approaches proposed for shallow embedded systems or piles. Therefore, the proposed research work offers a contribution to the topic in order to provide useful tools and formulae for seismic design of embedded systems, with special regard to foundations of large plane size, such as those adopted in nuclear industry. To this aim, the Finite Element (FE) method is adopted as a robust, reliable and rigorous tool for modelling SSI problems, properly accounting for sources of non-linearities, scattering phenomena, kinematic and inertial interaction effects, even if its use is limited by usually large computational costs. Taking advantage of these features, it is possible to avoid simplified assumptions and limitations to linear or equivalently linear soil behaviour, as frequently adopted in methodologies proposed in literature for dynamic analyses of SSI systems.
In this light, the main purpose of the thesis is to develop a comprehensive three-dimensional non-linear FE procedure that can accurately simulate the dynamic response of embedded SSI systems under earthquake ground motions. The procedure accounts for non-linear soil behaviour, discontinuity conditions at soil-foundation interface, wave propagation, energy dissipation, kinematic and inertial interaction effects.
The research aims at ensuring a balanced trade-off between accuracy and efficiency, rigour and feasibility of application. In detail, it focuses on the perspective of a reduction of computational costs, which represents one of the key issues for the FE method. Interestingly, the ambitious optimal combination accounting for all these aspects requires the investigation of numerical issues and the integration of structural, seismic and geotechnical topics.
The criteria for performing robust and reliable dynamic FE analyses with a reasonable computational effort and machine runtime are then investigated. The task is pursued in two ways, namely a global and a local one. For the first approach, a two-step sub-structuring procedure based on a modified version of the so-called Domain Reduction Method is proposed and implemented in a FE code in order to reduce the extension of the discretized domain. In detail, the procedure allows to apply the seismic excitation close to the region of interest in terms of effective forces and it is particularly advantageous for three-dimensional applications with respect to the original formulation of the problem.
The efficiency of the proposed FE approach is then improved, from a local point of view, by adopting an elegant and novel formulation for the non-linear modelling of soil behaviour. The proposed theoretical framework represents all classical yield and failure criteria for geomaterials by means of a single convex equation and results in an extremely efficient numerical algorithm for the integration of the constitutive law at local points of the discretized soil domain.
The implemented algorithm is then successfully exploited for numerical applications, which are usually characterized by either theoretical or numerical limitations. Numerical issues about requirements on both the size of finite elements and the extension of the discretized domain are also addressed, together with the introduction of proper absorbing boundaries in order to simulate the theoretical semi-infinite extension of the bounded discrete domain.
All above mentioned aspects are given proper consideration in the research and are implemented into a FE code in order to investigate the seismic response of embedded SSI systems. The case-study refers to a nuclear reactor power building provided with a seismic isolation system at the base and supported by an embedded foundation of large plane size. The choice of the structural system is strategic, since it is representative of a broad range of structural behaviours in seismic conditions. In fact, if the structure is assumed as fixed, inertial interaction effects prevail on kinematic interaction ones, which can usually be neglected. The same conditions are typically adopted for the analysis of structures resting on surface foundations or subjected to D'Alembert's forces (e.g. machinery or moving loads). Conversely, the introduction of a seismic isolation system at the base of the structure amplifies kinematic interaction effects with respect to inertial interaction ones, which are drastically lowered. Similar situations occur in case of seismic design of structures resting on deep foundations (e.g. high-rise buildings, offshore platforms), for which kinematic effects cannot be ignored. In addition, non-linearities above ground can be easily introduced, e.g. in the modelling of the constitutive behaviour of seismic isolation devices.
In the thesis, it is shown how the adopted formulation and the implemented numerical tools provide a contribution to the assessment and clarification of some main key issues regarding numerical FE modelling of SSI. Furthermore, due to the pursued integration of structural, seismic and geotechnical aspects, the comprehensive and versatile methodology proposed within the research work can be extended to other dynamic SSI systems and it can be adopted for renewing seismic design codes and for the validation of simplified approaches and methods provided in literature.