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**PhD Yearbook | 2020**

# DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
**Prof. Umberto Perego**

**Objectives of the Doctoral Program**

Structural, Seismic and Geotechnical Engineering (SSGE) encompasses disciplines and techniques allowing understanding, modeling and controlling the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials, materials for micro-systems and metamaterials), (b) structural systems (from civil and industrial structures and infrastructures 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 structural and material behavior 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 the behavior of geomaterials, tunnels and foundations, not to forget the topics shared with some branches of 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) structural safety under highly-variable actions; (c) behavior of geomaterials 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: a minimum of three full-time years' study and research activities; the development of a PhD thesis; the achievement of the minimum credits required in terms of PhD 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, consistent with the main disciplines dealt with in the Doctoral program, which will be reported 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 used 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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# LIFE-CYCLE SEISMIC RESILIENCE OF AGING BRIDGES AND INFRASTRUCTURE NETWORKS

**Luca Capacci** - Supervisor: Prof. Fabio Biondini

Planning proper lifeline management policies is a key task to satisfy the primary needs of communities not only under operational conditions, but also in a state of emergency. Road infrastructure networks play a key role in the emergency response to extreme events to ensure both a quick deployment of aids and resources to distressed communities and a prompt repair of the surrounding lifelines and buildings. Among the components within transportation systems, bridges are highly vulnerable to natural hazards and crucial to guarantee the network connectivity, as narrow and fragile ”bottlenecks” seamlessly interacting with the environment where they operate. Therefore, it is fundamental to relate the vulnerability of critical bridges and the impact of their damage on the operability of affected communities. This would allow covering the idealistic link across two technical dimensions: the function held by vulnerable bridges of mending the morphological tears throughout the urban fabric and the role played by vulnerable structural members to safely sustain the perturbations induced by hardly foreseeable load patterns.

In this context, resilience is becoming a driving concept for new generations of Building Codes and Standards, informing innovative trends and practical policies for design, assessment, monitoring, and maintenance of strategic structures and infrastructure facilities. In civil engineering, resilience represents the ability of infrastructure systems and lifelines to withstand the effects of extreme events and to recover promptly and efficiently the pre-event performance and functionality. Resilience is often quantified based on the definition of an overall measure of system functionality. The initial drop of functionality after the occurrence of the extreme event represents the system robustness. After an idle time necessary to design the repair activities, system functionality is progressively recovered by restoring the damaged components. Resilience is commonly quantified as the integral mean of the functionality profile from the time of event occurrence up to a fixed horizon time (Fig. 1). Furthermore, resilience of structures and infrastructure systems is generally investigated considering damage and disruptions caused by sudden extreme hazards, such as earthquakes. Nonetheless, damage can also arise continuously in time due to aging induced by aggressive environments and resilience of deteriorating structures and infrastructure systems depends on the time of occurrence of the extreme event.

The thesis focuses on the definition of a life-cycle probabilistic framework for seismic resilience assessment of aging bridges and road networks considering the uncertainties involved in the three constitutive components of risk analysis: seismic and environmental hazards, vulnerability of spatially distributed aging bridges, and exposure based on downtime and recovery of damaged network components. The initial damage induced by seismic events and its recovery process through structural repair is related to traffic restrictions to different road users. The vulnerability of aging reinforced concrete bridges exposed to chloride-corrosion is evaluated by calibrating time-variant seismic fragility curves based on Monte Carlo simulation and Incremental Dynamic Analysis with respect to different limit states, from damage limitation up to collapse. Depending on the environmental aggressiveness, bridges may suffer a significant reduction of structural capacity over time and exacerbate the impact of severe earthquake events at the network level. Then, traffic flow analyses are carried out over the road network to assess the post-event system functionality and the corresponding resilience under prescribed post-event recovery scenarios.

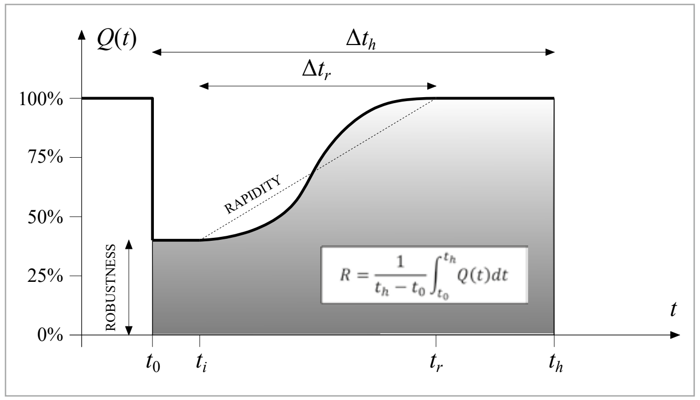


**Fig. 1 - Qualitative representation of functionality profile and system resilience.**

Archetype road networks with detours and re-entry links are investigated to demonstrate the capability of the proposed framework to assess the interdependency between seismic hazard scenario and environmental exposure of spatially distributed vulnerable bridges by means of the time-variant congestion-based measure of system resilience. The results highlight the impact of environmental aggressiveness in exacerbating the effect of seismic events on infrastructure resilience, increasing the likelihood of occurrence of large functionality drops and late restoration processes. The role of different factors related to bridge seismic capacity and network layout is discussed. The beneficial effects of infrastructure investments such as the upgrade of existing road networks with the construction of a new highway branch and the detrimental impact of climate change scenarios on exacerbating the lifetime bridge vulnerability and road network resilience are also investigated.

Novel computational approaches based on Importance Sampling and data reduction techniques have also been proposed to efficiently estimate the time-variant failure probability of deteriorating RC structures. In the proposed procedure, structural systems are efficiently simulated to account for the time-variant modeling uncertainties typical of life-cycle structural reliability problems. The method has been validated with practical examples concerning the assessment of the time-variant structural reliability of a statically indeterminate RC beam and the time-variant seismic fragility of RC bridges calibrated via multi-stripe analysis. The potentiality of the proposed sampling methods emerges when time-consuming analyses are required to define the mechanical response of the reference structure as well as when carrying out parametric analyses on random variables involved in the physical phenomena affecting in time the structural behavior, such as different temperature scenarios affecting the deterioration rate.

# STRUCTURAL BEHAVIOUR OF INNOVATIVE POINT-FIXING DEVICES FOR LAMINATED GLASS

**Marco Cervio** - Supervisor: Prof. Gianpaolo Rosati

Co-supervisor: Dr. Giovanni Muciaccia

Contemporary architecture is eager for transparency, therefore the last decades have been characterized by a significant expansion and evolution of glass applications in the construction industry. The application of point-fixing connections requires a great attention in structural design, techno-logical detailing, as well as in the specification of appropriate constructive tolerances, for both manufacturing and installation purposes. Therefore, the need of extensive testing to characterize and develop products and validate their related design methods. The mechanical characterization of an innovative embedded point-fixing device for use in laminated glass has been the trigger to develop a multidisciplinary, multi-level and multi-scale investigation. The research is based on the complementary use of experimental investigation and analytical models by resorting to appropriate idealizations and simplifications. Whenever possible, test results are also interpreted through numerical simulations, whose specific modelling assumptions are derived by experimental evidences. This research has the challenging ambition to propose a way different design and investigation methodology specifically dedicated to the study of point-supported panels. An easy safety assessment procedure, that in part try to overcome the issues pointed out in current design methods, is outlined. Despite its simplicity, this approach does not discard the essence of point-supported elements, that is the interaction between local and global behaviour.

The innovative fastener under investigation belongs to the family of “interlayer junction” embedded point-fixing devices (Figure 1). The fastener is bonded to the interlayer material and embedded in the glass panes during the lamination process. In fact, contrary to traditional point-fixing bolted connections, the countersunk hole is not passing through the outer glass layer and the stainless-steel insert looks like embedded in the glass mass preserving the beauty of “all-glass” and improving glazing performance. The advantages of mechanic and adhesive fixing solutions are here fully exploited. Moreover, stress intensification at contact points, thermal bridges, air and water tightness, durability and maintenance aspects are less crucial than in other types of point-fixing devices. Two different types of joint kinematics, which are intrinsically associated to the adopted point-fixing device connector, are investigated: (i) fixed-end stud bolt; (ii) hinged stud bolt. The proposed nomenclature refers to the apparent working principle, however the real kinematics of the joint and its modelling by means of ideal restraint conditions is one of the main goals of this study.

An extensive investigation of the fastener’s local behaviour was carried out with the aim of being aware of all the possible parameters and mechanisms which deeply affect the structural behaviour of the fastener in light of a critical design or assessment of point-supported panels. In this context, the aim of the experimental campaign was crucial and several tests were carried out to characterize the mechanical behaviour of the fastener, the resistant mechanisms and the type of failure transition (Figure 2). The latter aspect involves the fact that the type of failure changes from a local type, characterized by a cone failure of the system, to a global type, characterized by bending failure of the base material, depending on the specimen’s flexural stiffness.

The analytical study investigates the flexural behaviour of small-scale specimens, the axial stiffness of the point-fixing device and the state of stress within the interlayer. Through numerical simulations, the behaviour at the serviceability and at the ultimate limit state of the PFD was simulated. In addition, a collapse evolution model was also implemented (Figure 3). The collapse evolution model is the most appropriate to study the complex phenomena that brings the specimens to failure. In more detail, it allows to simulate the loss of adhesion, which is initiated by stress concentration on the outer circular crown of the anchor’s bottom surface, and the consequent activation of the undercut mechanism by progressive loading of the edge of the countersunk hole in the upper glass ply.

The global behaviour was investigated by means of experimental and analytical methods with the aim of study fastener restraining conditions and the effect of local-global interaction on panel deflections. The main outcomes are based on full-scale tests carried out on point-supported glass panels simulating a typical glass “canopy” configuration. The analytical study dealt with the evaluation of glass panel deflections adopting the theory of plates and considering for the laminated glass an appropriate equivalent monolithic thickness.

Following the aim of this research work a way different design and investigation methodology specifically dedicated to the study of point-supported panels is then proposed. Current design methods compute the failure stress as the superposition between local components and the global one, the latter multiplied by an appropriate concentration factor. The local behaviour is derived by numerical models that can be affected by errors or inaccuracies, hence an approach related to experiments rather than sophisticated models can be envisaged. This approach seems preferable because tests are anyway necessary for the product technical qualification. In this framework, the design strategy consists of two steps: (i) local verification comparing the load applied to the fastener with the interaction domain experimentally determined; (ii) global verification of stresses and displacements with respect to the tensile design resistance of the glass and limits given by the adopted design code, respectively.

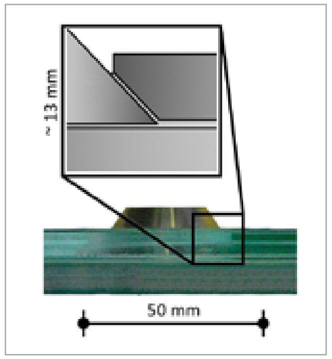


**Fig. 1 - Embedded point-fixing device based on the interlayer junction principle**

**Fig. 2 - Experimental investigation of the local behaviour**

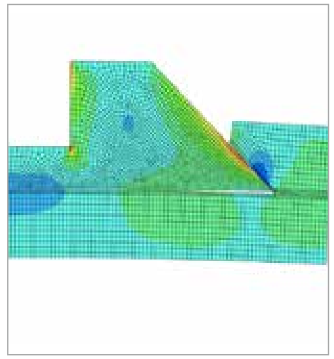

**Fig. 3 - Finite element model of the collapse evolution**

# A REGULARIZED CHEMO-MECHANICAL DAMAGE MODEL FOR STRUCTURAL ANALYSES OF CONCRETE DAMS IN THE PRESENCE OF ALKALI-SILICA REACTION

**Martina Colombo** - Supervisor: Prof. Claudia Comi

Concrete is one of the most used materials in civil engineering, but its durability can be reduced by several chemical phenomena, among them the alkali-silica reaction (ASR) plays a fundamental role. ASR is a chemical phenomenon that occurs over time in concrete between the alkaline cement paste and the reactive silica present in some common aggregates. This reaction causes the expansion of the altered aggregate by the formation of a viscous gel, which increases in volume when absorbing water: it exerts an expansive pressure inside the siliceous aggregate or at the interface between cement paste and aggregate, causing spalling and loss of strength of the concrete, finally leading to its failure. A lot of research effort has been devoted to describe the reactions occurring between aggregates and cement paste, to characterize experimentally the consequent expansion and to develop material models to describe the structural effects. These latter should be correctly predicted in order to assess the safety of concrete structures. Indeed, ASR can lead to serious cracking in concrete structures built several decades ago in very wet environment (e.g. dams), resulting in critical structural problems. It takes many years, however, for the reaction to occur and the symptoms to become visible. For this reason, the slow development of ASR can modify the stress state in large structures and induce an increase in the displacements and a pattern of diffuse micro-cracks.
The starting point of the thesis work is a bi-phase chemo-mechanical damage model, formulated in the literature in the context of multi-phase continuum constitutive models (with fracture energy pseudo-regularization). Damage-induced softening constitutive models, as the phenomenological one just mentioned, typically cause ill-posedness of the initial boundary value problems. Finite element solutions of such problems exhibit a sensitivity to the element size and do not converge to physically meaningful solutions as the mesh is refined. In order to introduce a remedy, various regularization techniques have been proposed in the literature (e.g. nonlocal integral models). The main objective of the PhD work is to develop and implement the nonlocal formulation of the bi-phase model. In particular, nonlocality has been introduced replacing strain invariants by their nonlocal counterpart, obtained by weighted average over a spatial neighbourhood of each point. This approach has been validated using 2D simple examples (samples with inhomogeneous material), then it has been applied to a real case of existing concrete gravity dam subject to ASR. This formulation, as the starting model, takes into account the simultaneous presence of temperature and humidity through two uncoupled diffusion analyses (the heat diffusion analysis and the moisture diffusion analysis) and it allows to evaluate the long-term degradation induced by the chemical phenomenon in real structures. The obtained results in terms of crest displacements and crack pattern have been compared with those computed by using the starting bi-phase damage model.
The second aim of the thesis is to define a link between the above phenomenological model defined at the meso-scale and a model describing the alkali-silica reaction at two different scales: the macro-scale and the micro-scale. At the micro-scale level, that project has allowed to study the evolution of the complex crack networks resulting from the ASR-gel formation process: it has been possible to identify the advancement of reaction at which the cracks, starting inside the aggregates, spread into the surrounding cement paste. On the other side, at the macro-scale the constitutive laws obtained from the micro-scale analysis have been integrated into simulations of ASR affected concrete dams. The two different scales have been coupled in a full multi-scale model. This strategy aimed at conducting simulations of the mechanical consequences of ASR in large concrete structures, in which the material behavior of concrete is directly governed by the physics of ASR occurring at the micro-scale.

In collaboration with two research teams of Politecnico di Torino and of École Polytechnique Fédérale de Lausanne, the multi-scale model has been extended to include the temperature effect and the results obtained have been compared with the phenomenological meso-model. In particular, several simulations at the micro-scale have been performed. First, omitting ASR evolution a validation of the multi-scale model at the micro-scale level has been made with simple tension and compression tests. Then, parameters governing this problem have been calibrated. Finally, a correlation between the two approaches from numerical point of view has been found.

# PULL-OUT OF CAST-IN-PLACE FASTENERS INFLUENCE OF THE BEARING PRESSURE AND STRUCTURAL INTERACTION WITH THE CONCRETE MEMBER

**Giuseppe Di Nunzio** - Supervisor: Prof. Giovanni Muciaccia

Co-supervisor: Prof. Gianpaolo Rosati

Construction detailing is the art of transforming thoughts and calculations into real objects. Experience allows the realization that poor structural details may implicate a rise in construction costs and even lead to the collapse of civil facilities. With this in mind, the importance of fastening technology is obvious. The structural engineer should be familiar with this technology in order to design safe and sustainable structures. Everyday thousands of anchorages are used to fasten structural and non-structural components to concrete structures. Depending on the use and on the design loads, both post-installed or cast-in-place fasteners are a suitable and safe solution in construction practice. The need for the re-use and rehabilitation of existing buildings is accelerating the development and the use of post-installed systems. There are, nevertheless, several applications in which cast-in-place fasteners are still preferred. A typical example is represented by hold-down bolts for steel framed structures or for industrial machinery. The use of fastening to concrete is growing faster than that of the improvement of methods for design and verifications. In particular, for concrete-related failure modes, current approaches result from a protracted debate regarding the relation of the peak load to the failure surface. Therefore, the methods were derived consistently with simplified assumptions on the influence of other parameters.
Within this context, this Thesis aims to provide a further insight on the behaviour of cast-in-place fasteners under tensile loading. Through a combination of literature review, experiments and numerical simulations, two key topics are investigated: (i) influence of the bearing pressure on concrete cone breakout and (ii) the structural interaction with the concrete member. The genesis of the current design approach for fastening to concrete is presented, demonstrating that it could lead to conservative or unconservative predictions, particularly for cast-in-place fasteners. Several refinement proposals from the literature are reported and commented. Concerning the interaction with the concrete member, inconsistencies for the verification of the local load transfer are highlighted. In fact, verifications for the concrete members are limited to shear only, neglecting the effect of splitting action and of induced bending. In addition, the influence of the geometrical layout is reviewed showing (i) a reduced group interaction and (ii) an enhanced disturbing effect due to close edges in case of low bearing pressure.
Four experimental campaigns are presented, in which cast-in-place fasteners of various sizes were tested in very different boundary conditions. The investigations encompass (i) pull-out tests with different fastener heads, pull-out tests with varying depths and with varying member thickness (ii) in presence of a confining pressure and (ii) in presence of cracks, (iii) pull-out of fastener groups and (iv) pull-out tests in presence of supplementary reinforcement. In ideal undisturbed conditions, it is shown that structural effects, as well as an increase in the load-bearing capacity, are mainly linked to differences in the bearing pressure (Figure 1). From the results of specific pull-out tests in totally unreinforced concrete members, it is demonstrated that the collapse is induced by the combination of splitting and bending actions. An estimation of the potential structural interaction is provided from pull-out tests in presence of cracks. Results from tests on groups of two fasteners are commented considering the effect of an uneven crack distribution intercepting the breakout body. Finally, pull-out failure is induced by preventing cone breakout in specimens reinforced with closely spaced stirrups. The experiments confirm that supplementary reinforcement are effective in preventing concrete cone breakout. However, the structural response is better predicted by a strut and tie model rather than the current design approach.

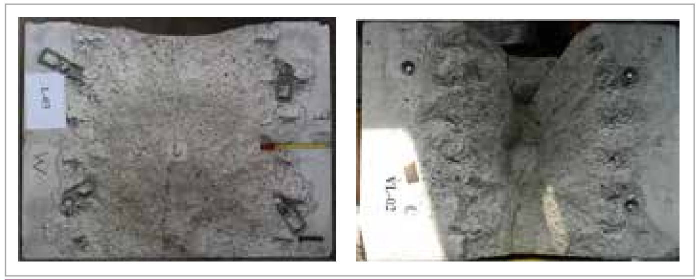

Fig. 1 - Two specimens after testing: (a) fastener with low bearing pressure and (b) fastener with very low bearing pressure.

Numerical modelling is introduced as a completion for the experimental study by simulating (i) the presence of free edges and (ii) the installation in members of various thickness. Numerical analyses were carried out using the commercial code ATENA from Červenka Consulting, licensed to Milan Polytechnic. In particular, GiD was used as pre-processor while solving and post-processing were carried out in ATENA. It is shown that numerical simulations represent a valuable alternative to laboratory testing when confronted with budget limitations. A continuum approach can be successfully adopted and, eventually, integrated with different strategies to model the presence of cracks intercepting the fasteners (Figure 2).

As result, a new refined approach is proposed for the pull-out capacity of the single fastener, as well as design recommendations for cast-in-place fasteners. The new approach aims to combine concrete cone breakout and pull-out failure in a single equation, the two mechanisms being connected through the bearing pressure. Design recommendations are suggested differentiating between two levels of approximation: *I level approach*, which is a more classic "force-controlled" design method and *II level approach*, which is a more innovative "displacement-controlled" design method.
Although with the inherent limitations of a single research study, the author believes that this Thesis may make a contribution in addressing open issues regarding the behaviour of cast-in-place fasteners and the relation to the structural response of the concrete member.

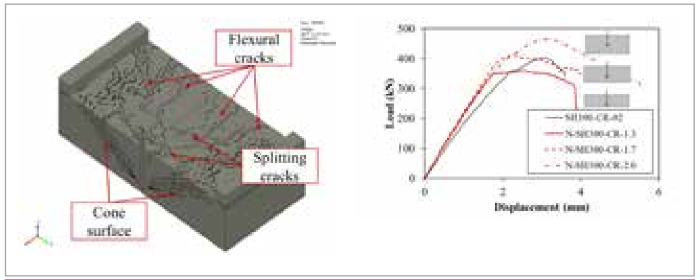


Fig. 2 - Results from numerical simulations in presence of cracks: (a) crack pattern (b) comparison of load-displacement curves.

# VIBRATION-BASED STRUCTURAL HEALTH MONITORING BY NOVELTY DETECTION AND FEATURE EXTRACTION TECHNIQUES

**Alireza Entezami** - Supervisor: Prof. Stefano Mariani

Tutor: Prof. Umberto Perego

Structural health monitoring (SHM) is an important topic of research areas in civil engineering due to the great importance of infrastructures such as high-rise buildings, bridges, dams, etc. The main objective of SHM is to evaluate the integrity and safety of these structures and diagnose damage including early damage detection, damage localization, and damage quantification. Recently, data-driven methods based on statistical pattern recognition present influential and efficient approaches to detect damage by using measured vibration data. These methods are generally based on two main steps including feature extraction and statistical decision-making. Time series analysis and distance-based approaches are effective tools for these steps. Despite advantages of data-driven damage diagnosis methods, those may give unreliable results of damage diagnosis due to false alarm and false detection errors. These errors may caused by some challenging issues including inappropriate feature extraction resulting from insufficient and inaccurate time series modeling under non-stationary vibration signals caused by ambient excitations, inaccurate statistical decision-making for damage detection due to the effects of environmental and operational variability and high-dimensional features. To deal with these issues, this dissertation proposes novel data-driven methods in the steps of feature extraction and statistical decision-making. The proposed approaches are related to innovative techniques for model order determination, residual-based feature extraction methods based on time series modeling, hybrid methods for feature extraction under ambient excitations and non-stationary vibration signals, several distance-based approaches to statistical decision-making for early damage detection, damage localization, and damage quantification. The effectiveness and accuracy of the proposed methods are validated by numerical and experimental structures along with several comparative studies. Results will demonstrate that the proposed methods in this dissertation are effective and robust tools for SHM of civil structures under environmental and operational variability conditions and ambient excitations.

**Keywords**
*Structural Health Monitoring; statistical pattern recognition; time series analysis; ambient vibration; non-stationary signal; damage diagnosis; novelty detection; high-dimensional data*

# THERMOMECHANICAL BONDING PROCESSES IN MICROSYSTEMS

**Seyed Amir Fouad Farshchi Yazdi**

Supervisors: Prof. Alberto Corigliano, Prof. Aldo Ghisi

Micro-electro-mechanical systems (MEMS) are widely be used in various industries. As meaningful examples, microscale accelerometers are used to monitor structures, micromirrors have been adopted in laser scanners and 3D imaging, gyroscopes in inertial navigation and control systems and micropumps in biomedical applications. Regardless of their application, microsystems need different stages of packaging in order to protect them from external hazards, for instance, mechanical impacts or chemical compounds. Among three levels of packaging, wafer-to-wafer level packaging is the first level, in which, the structures fabricated on one silicon wafer is protected by another silicon wafer. Silicon wafers can be bonded directly (direct bonding), by using an electric field (anodic bonding) or by exploiting another material as the intermediate (intermediate layer bonding).
Silicon Direct Bonding, also known as Silicon Fusion Bonding or Silicon Thermal Bonding, consists into joining two silicon wafers in contact without an intermediate layer and without external force. This method can be used with high temperature (above 1000 °C) and the wafers are bonded via Van der Waals forces, hydrogen bonding, capillary forces or electrostatic forces. In theory, every two wafers can be bonded in this way under the condition of flat surface. However, it is not always possible, since it is important to activate the surface before bonding by wet chemical cleaning. Based on the chemicals of the surface, the bonding can be subdivided into hydrophilic or hydrophobic. In hydrophilic bonding, there is a thermally induced oxide layer on one silicon wafer and a native oxide layer on the other. The hydroxyl groups (–OH) in the hydrophilic silicon wafers are polarized and the bond is initially created through the molecules of the water.
Electrostatic bonding or anodic bonding is a low-temperature (below 500 °C) bonding method in which the process is assisted by an electric field. The method was introduced by Wallis and Pomerantz in 1968. In comparison to direct bonding, anodic bonding is less sensitive to the sur- face roughness. On the other hand, due to the presence of a high electric field, there is the possibility to harm the microelectronic parts of the device. The principle of the anodic bonding is based on the polarization of alkali-containing glasses by applying a high DC voltage (400-1000V), while the wafers are on a hot plate with temperature between 350-450 °C. The alkali cations are moving toward the cathode, consequently an alkali-depleted region is made near the anode. A very high electric field at the periphery of the contact points pulls the nearest regions together and viscous flows of the glass make the wafers come into close contact. Large electrostatic field at the depletion layer creates a substantial electrostatic pressure, maintaining the wafers into contact. Then, chemical reactions at the interface lead to the oxidation of the silicon and atomic bonds between wafers.
The last category of wafer level packaging includes a third material as an intermediate layer to bond wafers. Eutectic alloys, soft metals, polymers, glasses and solders can be used as the middle layer in this method. Glass frit bonding belongs to this group. The advantages of glass frit bonding can be summarized in low temperature process, outstanding hermetic properties and high bonding strength. However, the main disadvantage of this method is the residual stress in the wafers after the bonding process. This residual stress makes the systems susceptible to mechanical failure in the further steps of the fabrication or during performance. Recognizing the sources and parameters causing residual stress is crucial in order to solve this problem.
First, the multi-scale parameters of glass frit, which are effective in the bonding process are evaluated. Microstructural study is performed to investigate the effect of chemical components and their morphology. Mechanical properties of the material are studied to use to obtain its elastic modulus and its hardness and finally, the surface topography of glass frit film on silicon wafer is measured. Second, the study of the mechanical reliability and the possible failure mechanisms of glass frit bonded system provides the fracture criteria data. By utilizing finite element analysis (FEA) and the experimental data obtained, a numerical model for bonding process leads to investigate the deformation and stress profiles, to identify the sources of the residual stress as well. The solution to reduce the warpage of the bonded wafers in terms of a new micromachining process is tested via the FEA model and as the result, it shows a significant reduction in warpage. Moreover, the experimental measurements also confirm this improvement by introducing this micromachining process before the glass frit bonding process.

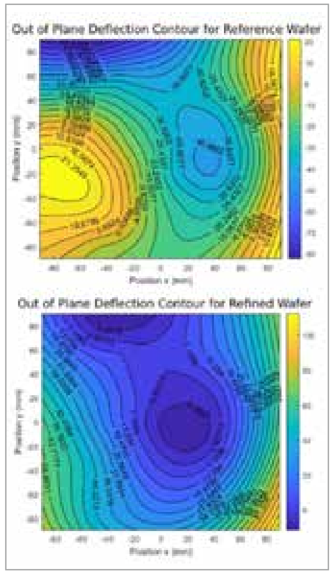


**Fig. 1 - The deflection contours in the out of plane direction, before and after applying the micromachining process.**

# PHYSICS-BASED PROBABILISTIC SEISMIC HAZARD AND LOSS ASSESSMENT IN LARGE URBAN AREAS

**Maria Infantino** - Supervisor: Prof. Roberto Paolucci

Besides being fundamental for defining seismic-design loads, probabilistic seismic hazard assessment (PSHA) is also preparatory to seismic risk and loss assessment. A key ingredient of any PSHA is the description of the ground motion attenuation. Empirical ground motion prediction models (GMMs), calibrated on the available strong motion records, are generally adopted for this purpose. However, the paucity of records in near-source conditions and the intrinsic limitations of the GMMs in fully accounting for the important physics effects that strongly affect ground motion in complex configurations, push towards other alternatives for those situations in which the GMMs are not well-constrained. As a matter of fact, physics-based numerical simulations (PBSs) of the strong ground motions have improved to the point of becoming an appealing complementary tool to GMMs.

In the framework of a research cooperation between Munich RE (Germany) and Politecnico di Milano (Italy), this work has a twofold scope: investigate issues regarding a reliable characterization of earthquake ground shaking by means of PBSs and explore different approaches in order to inject PBSs into PSHA. With reference to the first aforementioned intent, part of the research activity was devoted to improve computational tools aimed at generating broadband synthetic waveforms from low-frequency physics-based simulations, the latter obtained with the high-performance spectral element code SPEED developed at Politecnico di Milano. More specifically, a broadband approach based on the use of artificial neural network (ANN) has been proved to preserve a full spatial correlation of ground motion at territorial scale and on a wide frequency range.

The use of broadband PBSs in the perspective of a site-specific physics based PSHA allows a more realistic description of the specific features of fault geometry, local geology and morphology. Therefore, two alternative methodologies to directly incorporate PBSs into PSHA have been investigated. Starting from the work of Villani et al. (2014), a first approach, referred as GAF-based PSHA, consists of replacing the moments (i.e. mean and variance) of the lognormal distribution from the GMM with those obtained from lognormal distribution fitting the frequency histogram of PBSs at each site of interest. While a second method, denoted as footprint-based PSHA, involves the direct integration of the frequency-histogram itself of occurrences in place of the probability distribution. The two physics-based PSHA approaches produce almost identical results in terms of hazard assessment and/or loss assessment at a single site, while, conversely, their estimates differ remarkably when the loss assessment at multiple sites is of concern. Indeed, while the footprint naturally incorporates the spatial correlation features of the ground motion, the GAF requires the definition of a proper correlation model.

As main application to accomplish a comprehensive physics-based study (i.e. from the setup of the 3D numerical model up to a preliminary loss evaluation), the city of Istanbul (Turkey) has been selected among the large urban areas characterized by an high level of seismic risk worldwide. Thus, a set of 66 PBSs were carried out, considering earthquakes of magnitude ranging from 7 to 7.4 along the North Anatolian Fault portion, offshore of Istanbul. As main outcome we observed as, for increasing magnitude, PBSs estimate higher ground motion amplitudes with respect to the empirical site-generic prediction models mainly due to directive effects, consequence of the geometry of the North Anatolian Fault portion facing Istanbul.

# ON THE ROLE OF MATERIALS PROPERTIES AND STRUCTURAL CONTEXT IN REINFORCED CONCRETE MEMBERS EXPOSED TO NATURAL FIRES

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Fire is one of the most severe hazards that a structure can experience during its service life. When dealing with reinforced concrete members, fire can cause significant damage to the structure, but a complete collapse of a building is definitely rare, thanks to concrete incombustibility and favourable thermal properties. Given that most of the RC structures are able to survive the full heating-cooling phase, investigating the residual behaviour and suffered damage during fire becomes the priority.
Still, the current design practice focuses only on the heating phase, giving very little indication on the behaviour during cooling and in the residual phase. Nowadays, there is a tendency to shift from a traditional approach, based on standard fire, to performance-based design, which requires more accurate representation of the reality (i.e. a realistic fire scenario), in order to reach more effective and cost-effective solutions.
Most of the knowledge on the structural behaviour of RC members in fire comes from standard testing; therefore, most of the studies available in the literature are focused on the structural behaviour in the heating phase. Though several authors did research on the residual behaviour, there is no clear common background for performing analyses as regards fires involving heating and cooling.
This thesis deals with the structural analysis of typical reinforced and prestressed concrete beams and columns, on the basis of three different modeling approaches: sectional analysis, finite element analysis via beam elements and finite element analysis via 3D elements.
The aim of this thesis is twofold: (a) to investigate the role of materials properties in the cooling phase on the structural behaviour; (b) to give an overview on the possible modeling strategies, highlighting the particular aspects of the cooling phase. The obtained results showed that increasing the complexity of the numerical model does not necessarily lead to a more accurate prediction of the structural response. The focus should rather be put on the realistic definition of the fire scenario and the materials' mechanical properties in cooling.

# MODELLING AND SIMULATION OF PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS

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Ultrasonography was the first and the most important civil ultrasound application appeared in the 1950s. It is a non-invasive diagnostic technique, adopted to obtain images of human tissues by means of the principle of pulse-echo, that avoids the use of X-Rays scan, a technique that could be harmful because of the exposition to radiation.
Nowadays, array of several piezoelectric bulk wave resonators are employed in the commercial ultrasound imaging probes, in order to generate 3D real-time images. However, this technology is limited by the high probe manufacturing and material production cost.
Modern micromachining techniques allow for a much higher precision than the reticulation techniques, adopted for the fabrication of piezoelectric bulk ceramic elements and a more easily manageable fabrication of large 1D and 2D arrays that imply high resolution and real-time imaging capabilities, in spite of the very small amount of piezoelectric material. Piezo-MEMS technology has revolutionized the actuators and sensors world, leading the micromachining and miniaturization advantages in the ultrasound systems. Piezoelectric Micromachined Ultrasonic Tranducers (PMUTs), appeared in the first decade of the XXI century, consist of layered flexural plates with a piezoelectric thin film active layer, arranged in an array configuration, to emit and detect ultrasonic pressure waves. The possibility to replace the common piezoelectric bulk wave resonators with this novel technology, extremely increases the research interests in the study and the comprehension of its capabilities.
The main purposes of the thesis regard the modelling and the simulation of the Piezoelectric PMUTs working behaviour, in order to deeply investigate the acoustic performances of this device. Several multiphysics numerical models predict the behaviour of the stand-alone diaphragm and the array of transducers.
The attention is focused on the effects of the residual stresses related to the fabrication process and the DC voltage bias, V$_{DC}$. They both play an important role in the determination of the starting deformed configuration and of the fundamental performing frequency, which are strongly affected by the geometric stiffness. Additionally, the non-linear dynamic behaviour, due to the involved large displacements, is affected by the internal stress resultant and by the starting deflected configuration, as well. Subsequently, the non-linear response of the system changes with the imposed DC voltage bias. As a matter of fact, the PMUT center transversal oscillation shows a soft spring behaviour at V$_{DC}$ equal to 2 V, while it becomes a hard spring response at V$_{DC}$ equal to 12 V. The effects of the protecting structure in the acoustic performance, are deeply investigated. To this purpose a 3D Finite Element (FE) model is used to study the role of the vibrating package on the pressure propagation, considering its elastic properties. Furthermore, the acoustic-structure interaction is imposed on the transducers acoustic interface and on the package surface boundaries, as well.
Different numerical modelling techniques are proposed to solve PMUTs problems, reporting the main features, advantages and drawbacks of each of them. The experimental and numerical comparisons are presented, in order to validate the numerical models, together with critical aspects and discussions on the electro-mechanical-acoustic coupled response of the device.
The comprehensive electro-mechanical-thermoacoustic 2D axisymmetric model of the single transducer, correctly captures the quality factor of the system. The 3D electro-mechanical-acoustic model successfully simulates the in frequency response of the device. Moreover, the proposed 3D acoustic vibrating piston-like array of transducers allow for the estimation of the in-time pressure field, by means of the common commercial FEM acoustics software.
Furthermore, a novel piezoelectric-acoustic coupled FE Model Order Reduction (MOR) technique is described and successfully implemented into a Fortran custom code, in order to obtain a Reduced Order Model (ROM) of the PMUTs large array and to simulate the in-water response. To this purpose, the 11x11 PMUTs array transmitting (TX) phase and the 7x7 cluster of PMUTs receiving (RX) phase are simulated. The Reduced Order Model (ROM) custom code is characterized by extremely fast computational time with respect the hugely time-consuming standard full order FE approaches, implemented in the commercial software. Therefore, it represents a suitable tool to correctly evaluate the pressure propagation, the interference phenomena in the near-field and compute the response of the transducers in the actuation and sensing phases.