AEROSPACE ENGINEERING / ARCHITECTURAL, URBAN AND INTERIOR DESIGN / **ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING** / BIOENGINEERING / DATA ANALYTICS AND DECISION SCIENCES / DESIGN / ELECTRICAL ENGINEERING / ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY / ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING / INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING / INFORMATION TECHNOLOGY / MANAGEMENT ENGINEERING / MATERIALS ENGINEERING / MATHEMATICAL MODELS AND METHODS IN ENGINEERING / MECHANICAL ENGINEERING / PHYSICS / PRESERVATION OF THE ARCHITECTURAL HERITAGE / STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING / URBAN PLANNING, DESIGN AND POLICY

PhD Yearbook | 2022

Chair:
Prof. Marco Scaioni

DOCTORAL PROGRAM IN ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING

Vision
The Doctoral Program in Architecture, Built Environment and Construction Engineering (ABC) started in 2012 from the evolution of five older programs, active since the institution of the Italian Dottorato di Ricerca (PhD) in 1988. The aim of the ABC-PhD Program is to become a national reference point for training researchers and experts in the following fields:

- the sustainable transformation and management of the Built Environment, holistically viewed as an environmental, economic, cultural and social ecosystem, as well as time and space series of Architectures and cultural landscapes;
- the Engineering of buildings and components, structures and infrastructures, materials and service systems those architectures and landscapes are part of;
- the organization of the Industrial Systems that design, realize, manage and transform them and the Public Administration System that defines the rules for taking care of their value as social assets.

Program organization
The Program pursues the following ten pillars:
1) Selection through a transparent open process.
2) Candidates as independent, mentored and monitored, researchers.
3) Training plans tailored on Candidate's research topic and needs.
4) Training activities based on research practice.
5) Research practice hinged on the framework of Department activities.
6) Transparent tracking of Candidates' scientific production.
7) Systematic assessment and open and supportive peer review of Candidates' advancements.
8) Candidates as hot spots of international research institutions.
9) Systematic valorization of PhD holders and their products among stakeholders.
10) Candidates as active part of the Program's Quality Management System.

The award of ABC-PhD title requires that Candidates, under the control of their Supervisors:

- plan and carry out a three year, full-time, research activity;
- plan, attend and pass, with positive evaluation, a complementary series of Doctoral Courses, to complete her/his skills as researchers.
- develop a PhD thesis and defend it, in a Final Exam session certifying its original advancements on a specific topic.

For what concerns courseware, ABC-PhD Program boasts a wide (more than 20 titles/yr), diverse, educational assortment on cutting edge, specialized, research topics. It is an open list of courses that changes, year after year, following Candidates' needs as well as the opportunities offered by the Department. This list is further enriched with the transferrable skills courses offered by the PhD School and may be integrated by the offer of all the university Doctoral Programs.

Academic, industrial and social collaborations
Each Candidate is mentored by one main Supervisor and inherits Supervisor's Scientific Sector as reference. Due to the multidisciplinary nature of our wide research field, nevertheless, his/her activity may be supported by other co-Supervisors to make stronger, more sound and reliable his/her final research product. The main effort of the ABC-PhD Program Board is to keep Candidates research works constantly reviewed, involving every useful, available competency from the ABC Department, other Departments or other national and international Universities and Research Centers. Each Candidate is also assigned to a member of the Program Board, which serves as individual Tutor with the aim of constant independent monitoring of his/her activity.
Moreover, each Candidate is progressively encouraged to confront his/ her position, project, intermediate products and final results with any stakeholder that may acknowledge, enhance, valorize and exploit them through social or industrial collaborations. Our social and industrial collaboration starts often from the beginning: approximately 50% are thematic and the topic is defined (and the Candidate selected) together with an industry or an international research institution as funding – or co-funding – partner. Our mission is to train our PhD Candidates as self-sufficient and independent actors, able to gain – as scientist, as intellectuals, as professionals, as entrepreneurs – an outstanding position at an international level. We are sure that our early stage openness toward stakeholders and the whole scientific world and networks is the best way to provide future PhD Holders with solid occupational opportunities for an academic career as well as for an employment in research centers and in any other enterprise, public body or private societies in need of highly qualified personnel, in particular of experts trained to innovate and to manage innovation processes.
The PhD-ABC Program deals with a wide variety of topics and related disciplines. It is not possible to list them in few rows (see our site, here: https://beep. metid.polimi.it/web/abcphd/milestones) and it is even useless, due to our fluid, adaptable nature: we look for new research questions (in the wide ABC sector) and for good ideas to give answers to them. A complex set of cutting edge, scientific and humanistic, disciplines and experts are at Candidates' service to support them to make their efforts three-time-winning (Researchers, Stakeholders, Academy) intellectual products.

PHD PROGRAM BOARD

Marco Scaioni	(Surveying and mapping - ICAR/06) - Head of ABC-PhD
Andrea Antonio Caragliu	(Applied Economics - SECS-P/06) - Deputy Head and Delegate for ABC-PhD Training Programme
Oscar Eugenio Bellini	(Architecture Technology - ICAR/12)
Francesca Claudia Maria Belloni	(Architectural and urban design - ICAR/14) - Delegate for Milestones Organization
Elisa Boeri	(History of architecture - ICAR/18) - Delegate for ABC-PhD Training Programme
Francesca Bonfante	(Architectural and urban design – ICAR/14)
Maddalena Buffoli	(Hygiene and public health - MED/42)
Paola Caputo	(Building physics and building energy systems – ING-IND/11)
Valter Carvelli	(Structural Mechanics – ICAR/08)
Sara Cattaneo	(Structural engineering - ICAR/09)
Pierluigi Colombi	(Structural Mechanics – ICAR/08) - Delegate for Open Talks
Tommaso D'Antino	(Structural engineering - ICAR/09)
Laura Daglio	(Architecture Technology - ICAR/12) - Delegate for Web Communication
Claudio Del Pero	(Building physics and building energy systems – ING-IND/11) - Delegate for Milestones Organization
Stefano Della Torre	(Conservation and restoration of architecture - ICAR/19)
Maria Pompeiana Iarossi	(Representation of architecture - ICAR/17) - Delegate for promoting integrative activities of the PhD Candidates
Monica Lavagna	(Architecture Technology - ICAR/12)
Laura Elisabetta Malighetti	(Architectural engineering - ICAR/10)
Elvio Manganaro	(Architectural and urban design - ICAR/14)
Marzia Morena	(Architecture Technology - ICAR/12)
Laura Anna Pezzetti	(Architectural and urban design – ICAR/14)
Fulvio Re Cecconi	(Building Production - ICAR/11)
Corinna Rossi	(Egyptology and coptic civilization – L-OR/02) - Delegate for Milestones Organization
Matteo Ruta	(Building Production - ICAR/11)
Graziano Salvalai	(Architectural engineering - ICAR/10)
Leopoldo Sdino	(Real estate appraisal - ICAR/22)
Andrea Tartaglia	(Architecture Technology - ICAR/12) - Delegate for promoting integrative activities of the PhD Candidates
Marco Vincenzo Valente	(Architecture Technology - ICAR/09) - Delegate for Final Exam Committee

ADVISORY BOARD

Teresa Bagnoli	ASTER
Alessandra Faggian	Gran Sasso Science Institute
Mary McNamara	Dublin Institute of Technology
Catherine Maumi	École Nationale Supérieure d'Architecture de Grenoble
Agnes Weilandt	Bollinger + Grohmann Ingenieure

BOND DURABILITY OF FRP-CONCRETE AND FRCM-MASONRY JOINTS UNDER THE EFFECT OF ENVIRONMENTAL CONDITIONS

Karrar Al-Lami - Supervisor: Pierluigi Colombi - Co-Supervisor: Tommaso D'Antino - Tutor: Marco Vincenzo Valente

Fiber Reinforced Polymer (FRP) and Fiber Reinforced Cementitious Matrix (FRCM) have been increasingly adopted to repair and strengthen structural members in the last years. However, there is limited information available on their durability. The current research consists of two main parts aiming to investigate the performance of these two composites under hygrothermal and wet-dry conditions.

The first part was dedicated to studying the effect of the hygrothermal and wet-dry conditions on the CFRP-concrete joint and constituent materials (i.e., epoxy resin and CFRP strip). The hygrothermal condition was composed of continuous immersion in water at 38 ± 2 oC; however, the wet-dry condition comprised of 50 cycles with 6 hours of immersion in water followed by 18 hours of drying at 50 oC for each cycle. In total, eighty-two specimens were tested in this part of the research. Digital image correlation (DIC) technique was also utilized to determine strain profile, cohesive material law, and subsequently, fracture energy of the CFRP-concrete interface. A two-dimensional finite element model was also utilized to calibrate the obtained cohesive material laws so they could be implemented in any numerical model aimed to evaluate the durability of the reinforced concrete structures externally bonded with CFRP. The results of this part of the research indicated some visible and mechanical changes in the performance of the epoxy resin. Furthermore, the failure mode of the CFRP-concrete joints exposed to wet-dry cycles was changed from a cohesive debonding in the concrete substrate to an adhesive debonding in the interface. However, the load-carrying capacity of the joint was not significantly influenced.

The second part of the research focused on investigating the effect of the wet-dry condition on the FRCM-masonry joints. The specimens were prepared of three types of FRCM composites, which are made of carbon, PBO, and AR-glass textiles, and one type of Steel Reinforced Grout (SRG) composite. Both FRCM and SRG composites were externally bonded to masonry blocks. The specimens were exposed to 50 wet-dry cycles. Subsequently, the performance of the joints was evaluated using single-lap shear tests. The result of this part of the research implied some changes in the failure mode where it was changed for some specimens from a debonding failure within the matrix-fiber interface to a debonding within the matrix-substrate interface. Furthermore, the average bond capacity of all composites was affected in different ranges. The last section of this part of the research was dedicated to analytically simulate the behavior of the FRCM-masonry joints using a trilinear cohesive material law. The model has accurately simulated the behavior of the carbon and PBO FRCM-masonry joints that developed a debonding failure in the matrix-fiber interface.

SEISMIC RETROFIT OF RC FRAMED BUILDINGS WITH SUPPLEMENTARY ENERGY DISSIPATION: MODELLING AND APPLICATION OF A NOVEL LEAD DAMPER

Eleonora Bruschi – Supervisor: Virginio Quaglini – Tutor: Sara Cattaneo

The thesis develops tools for the seismic retrofit of reinforced concrete (RC) structures provided with energy dissipation devices. This aim is pursued by means of different subgoals, namely (i) assessment of reliable concentrated plasticity models for dynamic non-linear analyses of RC framed buildings; (ii) experimental investigation of a novel damper proposed for retrofitting RC structures; (iii) formulation of an effective and affordable displacement-based design procedure for proportioning the damping system in RC buildings; and (iv) assessment of the proposed method.

The first part of the thesis presents a critical review of current material modelling for ductile RC frame structures, in the context of non-linear time-history analyses, focusing on concentrated plasticity. Four RC frames with increasing number of stories (2, 4, 8 and 12) subjected to a set of seven spectrum-compatible input ground motions are examined numerically and the structural response is evaluated in terms of engineering demand parameters like base reactions (shear force and moment), inter-story drift and peak floor accelerations. Results of analyses conducted by adopting a distributed plasticity model are used as benchmark, and the implications of adopting different modelling assumptions to implement concentrated plasticity models in non-linear time-history analyses of ductile RC frame buildings are eventually highlighted and discussed.

In the second part of the work, a novel Lead Damper (LED) is experimentally investigated. The device provides a resistive force by the friction created between a lead core and a shaft. This damper is expected to incorporate several desirable characteristics, namely high stiffness and damping capability in a compact design and low manufacturing cost, which make it suitable for social housing. A modelling procedure is suggested to represent the non-linear behavior of the LED in both static and dynamic analyses. In particular, for dynamic analyses, a finite element object of the LED is formulated in the structural software program OpenSees.

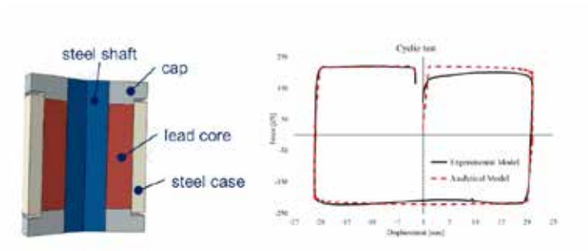

Fig. 1
Sketch of the LED prototype and fit of the analytical model to the experimental curve

Then, an effective and computationally affordable displacement-based design procedure for seismic retrofit of RC framed structures equipped with hysteretic dampers, characterized by an elastic-perfectly plastic behavior, is proposed. The method aims at proportioning damped braces to attain a target performance level (for a specific level of seismic intensity), controlling the maximum inter-story drifts of the structure and, if needed, regularizing the stiffness and the strength of the building along its elevation. In order to demonstrate its effectiveness, the procedure is applied to the retrofit of two existing reinforced concrete buildings. For the validation of the design method, the seismic performance of the retrofitted structures is assessed in both static and dynamic non-linear analyses. In particular, for the dynamic analyses, structural models are formulated in the OpenSees finite element framework by adopting a concentrated plasticity approach, based on the results of Chapter 1.

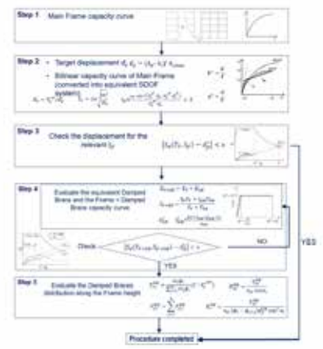

Fig. 2
Flowchart of the proposed procedure

In the last part of the study, the two RC structures are examined and retrofitted with the LED following the design procedure explained at Chapter 3. Two different design targets are considered: in the first case, the structure is retrofitted in order to maintain an elastic behavior, with no plastic hinges, during the earthquake, while in the second case, a partial dissipative behavior of the structure is allowed, with formation of plastic hinges limited to a repairable limit state. Non-linear dynamic analyses are carried out in OpenSees, considering a suite of artificial ground motions whose response spectra match on average the target spectra according to NTC 2018 for the life-safety limit state. The results of the numerical study demonstrate both the effectiveness of the LED device and the viability of the design procedure.

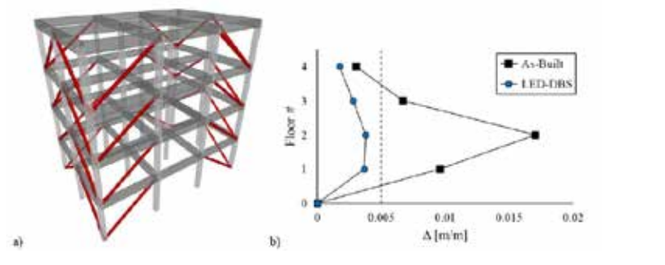

Fig. 3
a) case-study structure 1 retrofitted to guarantee an elastic behavior; b) results of the non-linear dynamic analyses in terms of maximum interstory drifts

CREATIVITY WHERE AND WHY. INNOVATIVE AND SPATIAL BEHAVIOUR IN CULTURAL AND CREATIVE INDUSTRIES

Roberto Dellisanti – Supervisor: Roberta Capello – Tutor: Andrea Antonio Caragliu

The analysis of Cultural and Creative Industries (CCIs) is not new in economics. In the last 20 years, a large amount of academic research put emphasis on the role of creativity for local economic performance, with pending research challenges especially because of its intangible and pliable nature. Especially CCIs have been identified as pivotal actors due to the recognition of their potential in stimulating socio-economic development. However, researchers still struggle in giving a shape to the founding nature of CCIs: creativity. Discussion around CCIs acknowledged that this concept is heterogeneous and difficult to capture, especially at the local level. In fact, creativity is forged by places, shaping its forms and intensity. Merging industries, creativity and space, this PhD work has a threefold aim, and it is divided into three main parts.

The first part of the Thesis reviews the main approaches to CCIs, using the way in which creativity is conceived as interpretative key. It retraces the evolution of the concept from its introduction until the most recent theories of the last years, detecting pros and cons of the current state of the art. Once set up the framework, a novel definition of creativity in CCIs is introduced highlighting two main aspects that will guide throughout the entire discussion. On the one hand creativity in CCIs is presented as a heterogeneous concept, translated into different creative outputs; on the other hand, the place-based nature of creativity is valorised, stressing on the idea that creativity is a peculiar territorial asset whose forms depend on the place. Culture and creativity depend on context conditions and cities and regions identify in their creative expressions. This first section ends with a novel conceptual framework where the definition of creativity is put in action. This represents the main conceptual advancement of the work. Hence, CCIs can be subdivided according to their capacity to generate creativity and this ability depends not only on the industry but also (and especially) on the place where the industry is located. In this way, *Inventive* CCIs are opposed to *Replicative* ones.

Building on the conceptual advancements, the second part of the work addresses the phenomenon of localization patterns of CCIs. What emerges is that the two key dimensions for a correct analysis of CCIs clustering are the heterogeneous innovativeness as well as the *filière* which they belong to. In fact, the creative and cultural *filière* describes a system of interconnections among players that is mirrored at the local level: different CCIs with different trade relationships benefit from different factors at the local level. Through a theoretical taxonomy combining the innovativeness of CCIs with the structure of trade relationships, the empirical analysis led to two main conclusions. First, the territorial factors triggering the spatial concentration of CCIs differ according to the heterogeneous creativity expressed. The capacity to innovate of CCIs builds on the cognitive local environment, feeding them to the generation and exploitation of new creative ideas. Secondly, the heterogeneity of CCIs is not only a matter of innovation but they differ also because of their *filière*. Thus, according to the involvement into the creative process, CCIs need different territorial elements. CCIs that mostly interact with other businesses have different needs compared to market-oriented ones.

Finally, the work discusses the stimulus that CCIs give to socio-economic development and the channels through which this happens. Results confirm that CCIs support growth, regardless their form and their heterogeneity. However, the territorial conditions that trigger this process are different, according to the capacity of CCIs to innovate. Furthermore, CCIs are also capable of triggering the economic resilience of places in periods of crisis. However, this strongly depends on the ability of CCIs to introduce into the economic system new innovations. New knowledge creation in CCIs is paramount to resist and recover from shocks. For this reason, policies devised to support the innovative capacity of CCIs are beneficial also for the economic system as a whole.

Therefore, this work attempted at entering the academic debate on CCIs under different perspectives. Conceptually, it merged two key features of CCIs, i.e. their heterogeneous creative capacity and the territorial roots of creativity, outlining a new framework for their classification. Empirically, instead, it rediscussed two key phenomena associated to CCIs: their localization choices and spatial concentration, explaining differentiated territorial conditions behind CCIs clustering; and the stimulus they give to economic growth and resilience, identifying different territorial channels promoting such relationships.

However, the work presents some limitations that need to be considered and used as a starting point for future studies. First, it is important to further explore the antecedents of the innovation performance of CCIs and their role as innovation trigger in other sectors considering other steps required in the process of knowledge generation and what role the territory plays in it. Second, future works could focus more in depth on some specific industrial segments of CCIs, in order to refine the interpretations and the considerations. Third, it will be worth to further explore the differences within *Inventive* CCIs, not deepened in these analyses, understanding the different socio-economic implications.

The results of this study have also some policy implications. In fact, local authorities should elaborate place-based strategies for the development of CCIs, considering their peculiar innovative behaviour and the specificities of the local areas. Policies should thus focus on the local factors attracting specific CCIs and the channels needed to generate growth in a systemic way. Plus, local authorities could set up specific commissions formed by representatives of both CCIs and other businesses in order to promote collaborations between CCIs and other actors, supporting the design of targeted policies and stimulating the awareness of the general public about the creative and cultural potential of the places. Finally, authorities at any geographical level may give support to CCIs in order to foster an inclusive 4th industrial revolution, unlocking their social potential.

THE VALUE OF STRUCTURAL HEALTH MONITORING IN EMERGENCY MANAGEMENT

Pier Francesco Giordano – Supervisor: Maria Giuseppina Limongelli – Tutor: Valter Carvelli

Motivations

Transportation systems support the development of communities and enhance the quality of life. In ordinary conditions, they allow the circulation of people and goods. During and after a damaging event, they provide life-saving and vital services. Nevertheless, gradual (e.g., corrosion and fatigue) and shock (e.g., earthquakes and floods) deterioration phenomena reduce the performance of critical components of transportation systems (e.g., bridges) during their life cycle. Careful management requiring multiple decisions, such as performing retrofitting, interrupting service, limiting service, must be implemented to maintain an adequate risk level. In turn, decision-making requires a decision model which should be able to include the uncertainty that affects the problem. The collection of information on the assets, using Structural Health Monitoring (SHM) techniques, can reduce such uncertainty, and ultimately support decision-making. SHM is aimed at assessing and tracking structural conditions in time so that the occurrence of anomalies can be detected. In the last decades, the interest in SHM techniques has grown increasingly. The possibility of automating the process of data management (collection, acquisition, transmission, storage, and processing) allows to obtain real-time knowledge of the state of structures. This characteristic makes SHM very appealing to support the management of transportation infrastructures in the aftermath of disruptions. Despite the advantages, SHM is not very widespread in practice for a series of reasons, namely:

- SHM has a cost (installation, maintenance, and management costs). Operators know the cost of SHM but lack adequate tools to compute its benefit;
- SHM does not enhance structural performances. Operators, which have a limited budget at their disposal, may prefer to pay for retrofitting works rather than investing in SHM systems;
- SHM results are affected by uncertainty. Operators could not trust SHM information.

A remaining issue in SHM is to convince owners and operators of infrastructures of what is the "added value" of SHM and what are its social and economic benefits.

Objectives

The main goal of this doctoral research is to provide a framework for assessing the benefit of SHM systems installed on the critical components of transportation networks, i.e., bridges, in the context of the management of emergencies following damaging events, such as floods and earthquakes. The developed framework is intended to support operators of transportation networks in decision-making related to the adoption of SHM systems on assets to optimize the allocation of economic resources and ultimately enhance the safety of users.

Methodology

The benefit of an SHM system is computed – before it is installed – through the Value of Information (VoI) from Bayesian decision analysis. Bayesian decision theory allows accounting for the uncertainty in both the decision problem (uncertain state of the structure) and in the SHM results (SHM outputs are not perfect) and to quantify the benefit of collecting additional information before it becomes available. In general terms, the VoI represents the reduction in the expected management cost associated with a given data acquisition strategy. The VoI can be used for the following purposes:

- Rank different SHM strategies by assigning to each of them a specific VoI before their installation. The most suitable SHM strategy will be the one associated with the higher VoI.
- Decide whether it is worthwhile to use a specific SHM method. The SHM system should be adopted only if its cost is below the assigned VoI.
- Consider the installation of an SHM system as any other possible action during the integrity management of structures. For instance, the operator may be asked to choose between performing retrofitting works or installing an SHM system.

Results

In this thesis, the topic of the VoI of SHM in the context of civil structures is investigated and expanded with respect to the available literature on this topic. The novelties regard the extension of the existing theoretical frameworks and several aspects of its practical applications that are highlighted in the relevant sections of the thesis. The problem is approached at the single bridge and at the network level. The developed framework allows quantifying the benefit of information from SHM collected before and after the damaging event. Two types of extreme events are considered which may produce emergency conditions, namely floods and earthquakes. Floods generate scour at piers which is considered the major cause of the collapse of bridges worldwide. Earthquakes affect large areas producing large human and economic losses. Further to this, the effect of aging and an aggressive environment inducing a progressive degradation of the bridge is accounted for. The relevant variables that influence the VoI are defined, modeled, and specified for exemplary case studies.

Figure 1 shows the typical results of a VoI analysis for demonstration. The case study relates to the post-earthquake traffic management of a bridge in a seismic area. Herein, two alternative management actions are considered, i.e., bridge "Close" and "Open" to traffic. It is assumed that after the selection of the management action, the structure can fail due to aftershocks. Figure 1(a) shows the optimal decision for the considered case study without considering the information from SHM in the framework of the Prior Bayesian decision analysis. The optimal action depends on the distance of the mainshock epicenter from the bridge R_m and its magnitude M_m. The VoI, shown in Figure 1(b), is maximum at the boundary between the two areas that correspond to different optimal management actions. Along this boundary, the two actions have the same expected cost which makes the decision difficult for the decision-maker. New monitoring information improves the knowledge about the structure state facilitating the choice of the optimal action. In this situation, the information from the SHM system provides the maximum benefit.

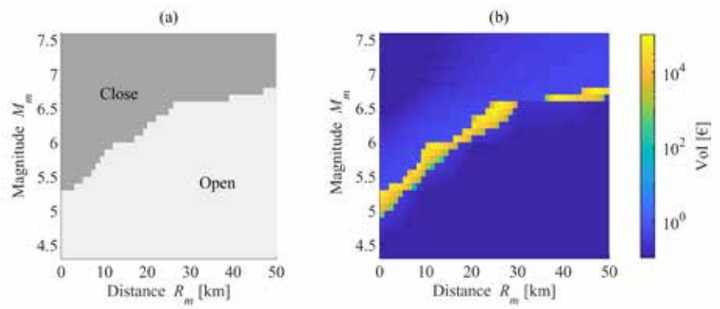

Fig. 1
(a) Optimal decision as a function of the distance and magnitude of the mainshock estimated (without considering the SHM information); (b) VoI as a function of the distance and magnitude of the mainshock.

CONSTRUCTION MANAGEMENT OF CULTURAL HERITAGE. CONSERVATION OF CULTURAL HERITAGE DURING ITS CONSTRUCTION SITE STAGE. BUILDING INFORMATION MODELLING SUPPORTING ON SITE INFORMATION COLLECTION AND MANAGEMENT FOR COST CONTROL

Luigi Guzzoni - Supervisor: Stefano Della Torre - Co-Supervisor: Giovanni Utica - Tutor: Marco Scaioni

Cultural heritage preservation and management is a complex domain, to which numerous and very diverse disciplines contribute specific, crucial competencies. Hence, cultural heritage represents a highly valuable experimental field, in which innovative management models and tools to govern complexity in general can be designed. Despite that, this perspective of cultural heritage management seems more fostered at the academic level instead of workplace. Moreover, this topic is more crucial on the Italian territory due to its history and the abundance of heritage buildings.

The whole construction sector is affected by a consequent loss in information and knowledge between the different stages of the life of a building. The fragmentation of information is also caused by the lack of synergy between each step of the process, which is treated in isolation from the other activities, as well as by the huge variety of the operators involved in each phase, which don't use a common language and software for data exchange. The trend entails an increase of costs and a waste of time to recover all this information. This issue is more critical and crucial with regards to the built environment, especially when involves conservation projects of a heritage building. Indeed, the knowledge of the building has to be recovered, implemented and continuously update, to be conducted to posterity.

Due to its multidisciplinary and organisational nature, Information Technology is now used as an instrument in the AECO industry to reduce some of the problems generated by its fragmentation. The most disruptive one is Building Information Modelling (BIM), a tool that allows a digital representation of physical and functional characteristics of a facility (digital twin). However, BIM for heritage assets (historic buildings and sites) is relatively new field and appears less popular in terms of adoption by heritage professionals.

In order to overcome the knowledge gap in the construction sector, in particular to improve data management of cultural heritage during construction site, it is decided to integrate the actual information management techniques with BIM for the purpose of improving efficiency and data management using dynamic database. For all these reasons, this PhD works adopted a constructive approach, a mixed method composed by seven steps: find a relevant problem that has research potential; examine the potential cooperation of target organizations; obtain a general comprehensive understanding of the topic area; innovate and develop a solution idea; test it in practice on a real case study; examine the scope of the solution's applicability; identify and analyse the theoretical and research contribution of the solution.

The research proposes a BIM-based approach for cultural heritage project in order to manage the construction stage of a conservation project. In particular, the research defines a proper protocol to deal with all information turn up during the construction site for a correct planned conservation.

This research focuses on the benefits that new technologies could bring to handle the construction process directly in the field. The scope of the research is to develop a new framework to gather all information from construction site via new technologies. The aim is to improve an accurate supervision of the site activities, to pursue a proper project control of construction stage, especially regarding the cash flow. In particular, this research work would support the Public Administration to improve and implement its actual procedures employing technologies already in use, for the cost management during construction site.

This PhD research presented a methodological approach aimed at enhancing artefacts' accuracy representation and information management in built heritage processes. For this reason, an HBIM model of the Teatro Lirico was developed to successfully represent both geometrical and information aspect of the facility. The result is a knowledge repository linked to a database that improves availability and accessibility of data supporting the conservation management process among different actors involved. The research combined the main advantages of BIM software, such as three-dimensional visualization, localization and precise quantification of each element and surface, with those offered by database applications, which allow information storage and organization in multiple ways, with the ultimate aim of obtaining a consistent and easily readable data framework. The application customized for the need of the Municipality of Milan, provide a new framework and tools to optimize the cost management and cost control process, in order to support and improve the Planned Conservation.

Moreover, the research seeks to strengthen precise protocols related to construction site activities regarding cultural heritage project in order to collect and manage all information required for the drafting of demanded documentation by Italian standard (scientific report for planned conservation) and create a unique knowledge repository of the cultural artefact, useful for the following usage and maintenance phase.

Lastly, the research aim of this PhD study is to generate conceptual constructs and practicable tools to facilitate structured BIM adoption by industry and academia.

PREVENTIVE AND PLANNED CONSERVATION. A RISK MANAGEMENT APPROACH TO THE BUILT HERITAGE

Anthoula Konsta – Supervisor: Stefano Della Torre – Tutor: Enrico De Angelis

Over the last thirty years, preventive and planned conservation approaches to the built heritage management have been gaining ground in the European context. Research and policy have marked a shift from isolated and episodic restoration interventions to long term processes of constant care and local development. Management tools and practices such as periodic maintenance based on regular inspection surveys and systematic monitoring, information management, risk preparedness, as well as systemic projects, valorisation strategies, and people involvement practices have emerged and have gradually been developed.

A paradigmatic approach is the Monumentenwacht model, based on the concept of supporting preventive conservation through a service of regular inspection surveys and the carrying out of minor, "first-aid", on-the-spot repairs. The organisation model, founded in the Netherlands in 1973 and subsequently in Belgium in 1991, has been studied and adapted to suit different statutory and cultural contexts by various European countries from the 90s onwards. Undoubtedly, the European standard "Conservation of cultural property – Condition survey of immovable heritage" (EN 16096:2012) follows the Monumentenwacht rationale and represents an attempt to implement preventive strategies.

In the Italian context, the definition of conservation as a long term process "ensured through consistent, coordinated, and planned activities of study, prevention, maintenance, and restoration", offered by the Italian Cultural Heritage and Landscape Code since 2004, provides a clear sense of the direction of development. The Italian approach to conservation is based on an integrated study of the cultural heritage and its environment, not only physical but also social-economic. The Pilot Project for the Planned Conservation of the Cultural Heritage in the Umbria region elaborated by Giovanni Urbani in 1975, the setting up of the Risk Map project by the Central Restoration Institution in 1992, the Guidelines for the Conservation Plan issued by the Lombardy region in 2003, as well as the ten-year Cultural Districts project in Lombardy represent the gradual steps and the considerable results achieved by implementing a preventive and planned approach to the built heritage conservation in Italy during the last decades.

What gains in importance in these examples is how to make rational decisions about cultural heritage conservation, or else how to make an efficient use of limited resources. The use of risk analysis, decision analysis, and risk management methods has been introduced in order to prioritise the activities, to reduce the costs and the losses, and to increase the benefits and the quality of conservation results. Under this perspective, these approaches have focused on the relationships between cultural heritage and its environment, as well as their changes over time.

Despite the new attitudes over the past three decades, procedures, tools, and methods have still to be clarified and formed explicitly. The purpose of this study is therefore twofold, on the one hand, to provide a better appraisal of the actual results, and on the other hand, to contribute to their improvement. The principal **research questions** are:

- What determines the different approaches to the risk management of built heritage?
- What are the most important aspects for the analysis of risks for the built heritage?
- What examples from other fields could be useful for the risk management of built heritage and what are the additional issues to consider for the built heritage?
- How is risk defined in the field of built heritage and how it can be measured?
- What methods of risk assessment are used, how they address the features of built heritage conservation, what are their limits, and how can be improved?

The research consists in a critical analysis of the various approaches to risk for the built heritage management, by characterising their key factors, by defining the concept of risk in the field of built heritage conservation, by investigating the process phases of risk management, and by classifying, comparing, and evaluating different assessment methods of risk. It is based on a literature review of built heritage risk management over the last three decades and of general risk analysis by taking into consideration different scientific fields. The research also employs two case studies for supporting the analysis.

The study is organised in two parts. A theoretical part regarding the risk management methodology for the built heritage and a practical one where the two case studies are used to illustrate how different problems are analysed and addressed. In detail, the **first chapter** provides a critical review of the most recent experiences that address risk management for the conservation of the built heritage. Three different categories, recommendations and guidelines, European projects, and best practices, both in the Italian and the international context, have been examined. The intention is to understand the different approaches, to put them into groups according to their common aspects, and to reflect upon the key factors in the risk management approach to the built heritage.

The **second chapter** discusses the classification of risks as a tool for the analysis, the assessment, and the management of risks. Existing typologies of risk vary according to the selected criteria on which they are based and their utility within the risk management process. Indicative examples of risk classifications proposed and used in the field of cultural heritage management, as well as in other fields, are examined. With the aim to frame a more methodical and holistic approach to the built heritage risk management, the different parts of a risk management process are examined, and their main characteristics, as well as their relationships, are underlined. Following this, different risk classification schemes are discussed with regard to their usefulness and practicality to respond to the process.

The **third chapter** concerns the review of the existent literature related firstly to the basic definitions of risk, its components, and subsequently to their assessment methods. The study takes into consideration the different risks to which the built heritage is exposed. The purpose is to gather the methods currently in use, which will permit to have an overall picture of the available methods and at the same time to identify the eventual gaps and the critical aspects of the research/practice, and make suggestions for their improvement.

The **fourth chapter** concerns a practical application of the different frameworks proposed for the analysis of risks. Two case studies have been selected, the historic buildings of the Park of Monza and the Milan Cathedral. These two case studies are very different, both for their dimensions and for the problems and the needs that present. This variety gives us the opportunity to be engaged with different scales of analysis and to set different objectives. In the first case, the question regards the failures of the rich stone decorations and the visitors' safety. In the second case, the problem concerns the risks related to the use (or non-use) of the historic buildings.

CONSTRUCTING PLACES AND COMMUNITIES. THE RELATIONSHIP BETWEEN ARCHITECTURAL AND URBAN DESIGN IN AGRO PONTINO.

Emanuela Margione - Supervisor: Francesca Bonfante - Tutor: Gianandrea Ciaramella

The thesis addresses the theme of New Towns and villages in the Agro Pontino starting from the objective of the European research project Modscapes, which analysed those international case studies that, in the early 1900s, conducted a transformation of the rural landscape with the aim of recreating the so-called *Modern Rural Landscape*.
The Agro Pontino is a geographical area contiguous to the Italian capital Rome and related to the project of *Bonifica Integrale* elaborated in 1923 by the agronomist and economist Arrigo Serpieri. The plan was developed to solve three main national social issues: the distribution of the labour force represented by veterans of the First World War; the high population density of Italy's major urban centres; and the reclamation of the considerable number of abandoned, uncultivated and marshy territories spread across the country.
What makes the Agro Pontino case study a model example in the international context is the extraordinary role played by architecture and town planning in the search for a new experimental relationship between the countryside and urban areas capable of solving the problems described above. However, the role of architectural and urban design has not been widely explored in the scientific literature as it is often shadowed by the so-called political bias.
Starting from these premises, the thesis offers a new interpretation of the case study by investigating the topics from an architect's point of view or, in other words, by highlighting those essential compositional elements that characterise the landscape transformations, urban planning and architectural design of the new settlements in the Agro Pontino.
To return this innovative narrative, the thesis is structured into six chapters.
The first chapter *Introduction* is dedicated to the methodologies and tools applied to develop the research work. The second and third chapters describe the framework in which the Agro Pontino project is developed. Specifically, in the second chapter, *A critical literature review*, those contradictions within the literature that have allowed the determination of the centrality of themes related to architecture and urban design are highlighted, while in the third chapter, *New Cities between theories and practices*, are pointed out those themes whose definition is essential to understand the main choices adopted within the projects of new settlements.
In the fourth chapter, *Agro Pontino: the territory that was built and then theorized*, the modernist rural landscape and the new settlements are described starting from a main question: how were they designed? Often the literature dedicated to the Pontine settlements, focusing on general issues, and framing the case study within the national debate, tends to return an image of the New Towns understood as entities randomly sprung up in an uninhabited territory. However, thanks to a more careful reinterpretation of the original materials it was possible to describe both the origins of the integral reclamation project and the essential characteristics of what can be considered as a new (R)*urban prototype*. In particular, within the thesis the territory of Agro Pontino is defined as a real palimpsest in which the physical pre-existences and the new experimental urban planning theories from the Thirties play a fundamental role in the design of the New Towns.
In the fifth chapter, *Experimental aspects of Modernist Rural Architecture in Agro Pontino*, two fundamental issues are outlined: the contributions of the case study in the definition of those new architectural typologies arose in the Thirties such as the *Casa del Balilla, Casa del Fascio, Casa del Contadino* etc; the role of architectural composition in the creation of the particular urban space realized to host a new community. Specifically, the experimental aspects of the buildings realised in the new towns and villages of Agro Pontino are outlined through the description of the close correlation between the design call and architectural handbooks published in those years. For a clear reading, the buildings are divided into three main categories: the new architectural typologies in which it is the level of typological experimentation that defines their role within the urban project; the public residential buildings which, although not subjected to a particular architectural experimentation, play a fundamental role in the composition of the urban space; the technical-administrative buildings in which, instead, it is the landscape dimension that becomes central.
Finally, in the sixth chapter *Conclusions* the summaries of all the issues dealt within the thesis are drawn. In particular, it is highlighted how through this new reinterpretation of the case study is possible to conceive the experience of the new settlements of Agro Pontino as an interesting design exercise still applicable today to rethink a new relationship between city and countryside and between city and urban public space both in Italy and abroad.

Fig. 1
Author's critical reconstruction of Agro Pontino territory in 1940 after the Integral Reclamation process

Fig. 2
Author's photographic survey 2018. Elementary school in Sabaudia by Oriolo Frezzotti (1934)

THE COST OF NOISE FOR LEARNING
A PRIORITY-SYSTEM FOR PUBLIC SCHOOLS MANAGEMENT

Stefania Masseroni - Supervisor: Giovanni Utica - Co-Supervisor: Massimo Guazzotti
Tutor: Enrico De Angelis

In the European Union, about 100 million people are exposed to noise pollution, most of them with health consequences and learning performances depending on different sound sources to which they are daily exposed. By the way, with the contemporary change rate of transport systems, the necessity for noise insulation and noise reduction policies has become a crucial theme. Actually, noise is a critical environmental issue strongly perceived by the population. This research focuses on issues relating to the effects of noise on children at school, during learning time.
Areas covered include the effects of environmental noise on children's academic performances, noise surveys about environmental outdoor noise levels and school buildings construction technologies.
Nevertheless, the method is supposed to be applied to any kind of acoustic source, the thesis mainly addresses to aircraft noise pollution. Thus, the research includes quantitative methods such as noise surveys and the study of National, International Best Practices dealing with building acoustic insulation cost. Then, the study addresses qualitative methods, analysing Invalsi tests performed by students in the noise-polluted area.
Firstly, the analysis means to understand how comfort inside buildings changes according to outdoor noise pollution and how acoustic design changes according to noise nuisance perception. Besides, the research deals with the proposal of specific adaptation terms for air traffic sources. Then, a comparison between noise levels and Invalsi tests is performed, in order to define, if any, the relationship between noise pollution, buildings construction technologies and children's education.
The proposal of a new adaptation term about air traffic noise, after a specific noise source analysis, could improve performances inside buildings after the noise abatement at receiver, also giving an economic quantification of it. This could be useful for public entities or even private ones, who wants to adapt an obsolete property stock to the new standards of comfort.
In the end, the use of a priority index considering all the previous variables could lead public Municipalities to choose among a wide asset of building those with a higher priority for intervention. This research intends to propose a focus on noise insulation directly at receivers, by performing an analysis about a sample of school buildings and their state of conservation located in the proximity of an International airport.
The large majority of existing buildings need to be adapted to current regulations with new comfort levels for the buildings users. This allows renovating a consistent part of public buildings, with no new land construction according to European Directive about soil consumption.
Any form of noise pollution has its own identity, developed by frequency, which has to be evaluated specifically, identifying recommended insulation properties. In this way, European Regulation provides for adaptation terms, based on noise spectral characteristics (C; Ctr). The use of those terms, allow choosing better conditions for the building envelope insulation.
Since the cited terms relate to human noise (C) and road traffic noise (Ctr), the introduction of a new aircraft-noise adaptation term takes into account the specific connotation of this noise source.
The quantitative analysis focuses on LAeq and LAmax parameters. By the way, the European Environmental Agency provides LAmax as one of the most important indicator of noise annoyance. In order to determine a new adaptation term focused on aeronautic noise spectra, the procedure was the Standard UNI EN ISO 717-1.
Then, the qualitative analysis involves the primary school buildings located in a range of 10 km from the airport. The school buildings have been placed in the simulated isophonic curves map. As a result, it is possible to simulate the external LAmax value for each school.
To compare LAmax levels and student performances, the analysis considers the INVALSI (Italian National Institute for Educational Evaluation) tests results. Considering the wide asset of school buildings managed by Municipalities, the thesis proposes the use of a revised priority index in order to follow a general guideline to give to each building a different priority of intervention. The definition of the priority index starts from the formula proposed in DM 29/11/2000.
To consider the comfort inside a school building two indexes have been introduced: the INVALSI index and the Building index. The INVALSI Index takes into consideration the INVALSI results achieved by students in each school in comparison to the regional average. The Building Index considers the state of preservation of the building focusing on four main technical elements, which are: Vertical Main structures; Roof; External plaster and wall coverings and Windows and external doors.
Applying the formula to every building involved in this analysis, it produces a list to give the priority of intervention for schools in noise polluted areas, according to their state of preservation, their students' performances and their exposure to aircraft noise. Using this index Municipalities can finally establish a priority, starting from schools with the highest need of interventions.

CYCLIC COHESIVE ZONE MODELLING OF FATIGUE CRACK PROPAGATION IN METALLIC ELEMENTS STRENGTHENED BY CFRP PLATES

Mana Mohajer - Supervisor: Pierluigi Colombi - Co-Supervisors: Massimiliano Bocciarelli, Giulia Fava
Tutor: Valter Carvelli

An increasing number of ageing steel structures subjected to fatigue loading are reaching the end of their service life. Demolishing and replacing the old steel structures costs significantly more compared to the design and installation of proper strengthening systems. For this reason, carbon fiber-reinforced polymer (CFRP) composites have been widely proposed and successfully utilized as an efficient technique to strengthen existing steel structures which are either currently fatigue damaged or close to their fatigue lifetime. Therefore, dealing with crack propagation, as a fundamental failure mechanism in the presence of fatigue loading, has become crucial for a reliable design of these strengthening systems. In addition to the several experimental scenarios in the literature aiming to propose the most efficient CFRP strengthening system, different numerical models have been proposed to investigate fatigue crack growth in CFRP-strengthened steel structures. They mainly refer to empirical damage accumulation rules (S-N curves) and fatigue crack propagation models based on Fracture Mechanics concepts such as Paris' law. As an alternative approach, the computational assessment of fatigue crack growth is studied in this research work by using an irreversible cyclic cohesive zone model (CCZM). This nonpotential damage-based CCZM is implemented in Abaqus software as a finite element-based software through developing a user-defined element (UEL) subroutine in Fortran. The key advantage of cohesive zone modelling is the definition of a constitutive behavior, so-called traction-separation law (TSL), being assigned to the crack surfaces which leads to study the process of crack initiation, propagation and retardation as a gradual progressive phenomenon. Two sets of parameters namely, material parameters and fatigue parameters, configure this CCZM. While material parameters represent the material properties of the region where crack is propagating through, fatigue parameters control the crack propagation due to unloading-reloading cyclic loading. Fatigue parameters of the model are also correlated to loading conditions such as loading ratio. In particular, in addition to the dominant softening behavior of cohesive elements, the local increase in the stiffness which takes place due to crack closure effect during the unloading phase is taken into account as well.

Furthermore, the rate of damage evolution is scaled through modifying two fatigue parameters of the implemented irreversible cohesive zone model. This feature enables the linear extrapolation of damage variable which is indeed of advantage dealing with the simulation of high number of loading cycles.
After development of the UEL subroutine to define the desired constitutive law which enables the numerical study of mode I and mixed mode I/II fatigue crack, the validation was performed with respect to different experimental evidence in terms of the geometry of specimens, CFRP strengthening systems and stress ratio of constant amplitude loading history. Initially, the experimental results corresponding to unstrengthened and CFRP-strengthened precracked middle-cracked tension (MT) specimens subjected to fatigue loading are simulated. This part of the work focuses on the prediction of performance of unbonded prestressed CFRP strengthening system to further enhance the strengthening system functionality, and to promote the crack arrest leading to the increase in fatigue lifetime of the steel elements as well. In addition, the nonprestressed bonded CFRP-strengthened MT specimens are modelled by including two failure mechanisms in one analysis: mode I fatigue crack growth in the steel, and the CFRP debonding at steel-CFRP surface. In this model, CCZM for crack growth in steel and a bilinear TSL for debonding of CFRP plate are coupled to present the efficiency of the proposed method.

In order to further verify the potential of the developed model being used in different geometries, material and load conditions, the simulation of mode I fatigue crack growth in unstrengthened and CFRP-strengthened single-edge notched tension (SENT) specimens has been performed. Due to the several parameters which configure the implemented cyclic CZM, in particular, fatigue parameters which, to the Author's knowledge, do not have a physical definition, the inverse analysis approach, based on the nonlinear least square method, is performed for their identification in relation to mode I fatigue crack growth studies.
The structural elements may experience the initiation and propagation of mixed mode crack which, to the Author's knowledge, has not been widely investigated by numerical analysis. As for another objective of this research, the primary tools of finite element-based cohesive zone modelling of mixed mode fatigue crack is provided. A preprocessing MATLAB code is developed to insert automatically the CZ elements with different alignments in a wide area which is the potential region for mixed mode crack kinking and crack growth path. The developed preprocessing code can be further used along with the arbitrary cohesive zone model. Several potential zones where crack may initiate and grow could be considered through preprocessing. The fundamental outputs of this supplementary code in the FE simulation of cracking under mixed mode I/II loading is the configuration of the required CZ elements and the modified connectivity of the continuum elements.

Although the developed MATLAB preprocessor combined with the developed UEL is used to capture mixed mode I/II crack kinking, the prediction of the whole crack path in mixed mode I/II condition under fatigue loading is out of the scope of the current research work.

Based on the achieved results, the following conclusions can be pointed out:

- After calibration of the cyclic cohesive law for fatigue driven crack propagation, with respect to the unstrengthened specimen, the implemented cohesive model can be successfully adopted to investigate other configurations, such as steel specimens strengthened with CFRP patches, both prestressed and nonprestressed.
- A good agreement between the numerical and experimental results is observed for the CFRP-strengthened MT specimens, as well as SENT specimens, which permit to validate the adopted cohesive zone model.
- The proposed numerical approach can simulate both the bond behavior between the strengthening patch and steel substrate, and fatigue crack growth, during one analysis. A fatigue-compatible CZM is implemented to model the fatigue crack propagation in the steel substrate and implemented in Abaqus FEA through the development of a UEL subroutine. Additionally, the surface-to-surface contact model available in Abaqus is used to model the steel-CFRP interface debonding. Finally, the crack retardation and potential crack arrest in the steel bulk material are captured by the adopted properly calibrated CCZM.
- Parametric studies on the bond-slip law used in the simulation of MT specimens as representative of the adhesive behavior reveals the dominant effect of higher value of TSL's initial slope in the extension of fatigue lifetime; either by increasing the bond shear strength or by decreasing the critical displacement. In addition, the results show that the duration of fatigue lifetime has a direct relationship to the stiffness of strengthening system.
- Towards the calibration of CCZM parameters, updating the FE parameters can be achieved by performing an inverse analysis to minimize the difference between numerical and experimental fatigue crack growth curves.
- The combination of the developed MATLAB preprocessor and UEL subroutine is capable of capturing mixed mode I/II crack kinking in steel specimen subjected to cyclic loading, which occurs at the beginning of the crack path starting from the inclined notch.

IMAGE-BASED MULTICAMERA MOBILE MAPPING SYSTEM TO SURVEY NARROW SPACES

Luca Perfetti - Supervisor: Francesco Fassi - Tutor: Marco Scaioni

Nowadays, complete 3D digitalisation, the process of acquisition and processing of 3D metric data, has become almost a fundamental step in many fields such as cultural heritage, land survey, infrastructure, archaeology, city planning and others. In all these fields complete 3D modelling is the base for several application such as the creation of digital twins and virtual documentation, Building Information Modelling (BIM), Geographical Information System (GIS), restoration projects, valorisation project, virtual reality and augmented reality (VR & AR), and in general for long term management and monitoring of different assets.
There is, therefore, a strong demand for complete and accurate 3D measurement of objects such as buildings, manufacts, infrastructure etc. to be acquired and updated in the shortest amount of time possible. Nowadays, there are already different instruments and techniques that allow for the acquisition of 3D data and high-resolution images, above all, among the most popular: terrestrial laser scanners and close-range photogrammetry. However, the available technology is not suited for all application that the market demands.
The final goal of creating a digital copy, a digital twin, of everything, hits a barrier in the 3D mapping of very complex areas, above all: narrow and extensive spaces such as tunnels, spaces that can be found everywhere and are a necessary component of the aforementioned fields. Narrow spaces such as passages, staircases, tunnels, mines, catacombs, caves and the like have similar characteristics and can be found both in hand made environments and natural formations. The limited accessibility of these spaces prevents the mapping operations completely or makes them economically unsustainable for the state-of-the-art technology and tools by requiring too much time to be completed.
The research work has therefore focused on the realization of a multi-camera survey tool that can complete the acquisition of data in complex areas with ease and in a short time and that at the same time can guarantee high levels of accuracy and reliability.
The first phase of experimentation was based on the use of fisheye photogrammetry and the design of different low-cost multi-camera solutions mounting GoPro cameras with fisheye optics in order to exploit the advantage given by the angle of view. Subsequently, these first experiments led to the formulation of the FINE Benchmark, a dataset designed and shared with the scientific community with the aim of highlighting the limitations of a low-cost approach based on commercial sensors. Finally, the last phase was the design of a multi-camera system to improve on previous iterations. This was achieved by analysing the GSD (ground sample distance) distribution in the image space of the 5 cameras composing the multi-camera and in the object space, on the object surfaces at operational condition. This led to the creation of a working prototype that allows three-dimensional reconstruction and photographic inspection of confined environments, both man-made and natural. It is specially designed to ensure high accuracy and repeatability of the survey. The multi-camera finds its natural application in those situations where a 360-degree digitization is required, with high-resolution 3D geometric information and complete photographic documentation. The device is able to acquire 3D data in the form of point clouds and high-resolution images to describe the area of interest in a short time.
The instrument consists of a multi-camera designed to be used by hand by a single operator walking through the environment/tunnel to be surveyed, or to be used autonomously when mounted on a vehicle or unmanned system.
After the design phase, several challenging case studies have been chosen as test-field to evaluate the performance of the proposed solution. The tests performed have demonstrated the effectiveness of the instrumentation in achieving its objectives of speed and accuracy.
The design and characteristics of the multi-camera system have led to the filing of a patent application in January 2021 (Application No. 102021000000812). In addition, the solution produced was one of the winning finalists in the Switch2Product acceleration program organized by PoliHub, Technology Transfer Office of the Politecnico di Milano and Officine Innovazione of Deloitte.

Fig. 1
Images of some narrow passages inside the Milan's Cathedral and of the first prototype of the proposed device employed during the survey operations.

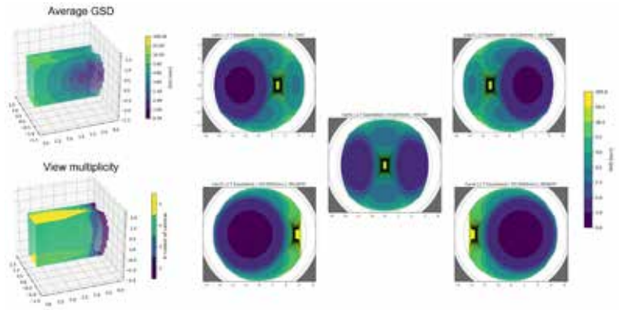

Fig. 2
GSD analysis performed during the design phase of the device. GSD destitution simulated in object space (left) and image space (right) for all five fisheye cameras composing the system.

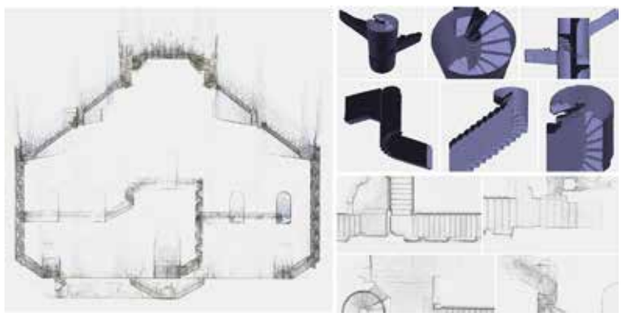

Fig. 3
Results of the 3D reconstruction of some narrow passaged inside the Milan's Cathedral. Elevation view of the point cloud (left), plan view (bottom right) and 3D view of the mesh model (top right).

THE DESIGN AT THE CORE OF HOUSING PROJECT. OVERCOMING PRECLUSION TO INDUSTRIALISATION BETWEEN RESILIENCE AND SUSTAINABILITY. CRITERIA AND CATEGORIES

Gianluca Pozzi - Supervisor: Elisabetta Ginelli - Tutor: Fulvio Re Cecconi

The research aims to demonstrate the central role of the design and its relevance in giving value to project. This is mostly true nowadays, because of the fragmentation and the parcelling out of design process, often farmed to sectorial expertise, which cannot have a unifying and valorising vision of all involved components.
The design process of today must accept complexity as the only project charter able to overcome division and segmentation of construction.
The thesis concentrates upon building industrialisation's meaning and development path, for which Industrialised Building System (IBS) is an essential means to face to-day's living requirements, in particular sustainability and resilience, to which only full organic processes and off-site dry-joint buildings can give appropriate answers, as the thesis demonstrates.
The research defines the domain, the potentiality and the limits of pre-fabrication and industrialisation of today, also introducing design-centred building process categories as tools for analysing and managing the project and for evaluating and comparing different design approaches and techniques. The research has a double path: a deductive one and an inductive one. Deductive path starts from Technological Design Culture domain and theories, from sixties to nowadays researches, concentrating on design process analysis and terminological framework. Inductive path starts from data and statistic on buildings pre-fab market and the project cHOMgenius, trialling and testing shipping containers for housing, highlighting the criteria and the strategies to re-make the design phase sustainable, pro-active and resilient. Both paths support and reinforce the main idea that the role of the design is central in today's building house market and give criteria to evaluate the project.
A third parallel path can be underlined as a terminological one: there are many contradictions and grey-zones in definitions of categories linked with industrialisation, pre-fabrication and pre-assembly. This work proposes a possible clarification and fixed points on these aspects of the topic aspect (Fig. 1).

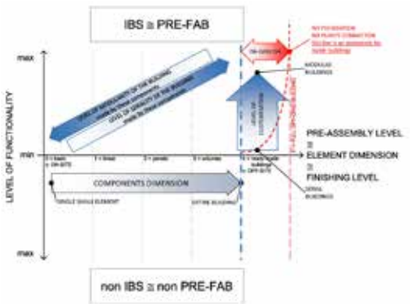

Fig. 1
Flexible visual graphic proposed for the classification of construction systems.

The thesis considers Shipping Container Building (SCB) for housing a good example of the ambition the design should pursue for current and future market. Inside SCB, this research has supported the project "cHOMgenius. PrototypeSystem&SharedProject. Extraordinary solutions for smart living" (https://www.dabc.polimi.it/en/ricerca/ricerca-competitiva/chomgenius-prototypesystemsharedproject/), partially funded by Regione Lombardia Smart Living. It is a two floors permanent residential building, entirely dry-joint with clamping techniques, built off-site using HC shipping container, off-grid and entirely dismantling and reversible. The very high performances achieved are the result of the sharing of objectives, right from the first design phases, of 22 companies, in addition to the scientific support of the DABC of the Politecnico di Milano and UNI. This project demonstrates that a particular approach to the project can produce sustainable buildings (from an economic, environmental and social point of view), resilient and, at the end of life, easily re-convertible, re-usable and recycling, thanks to the re-use of transfer objects and dry-joint clamping, by an oriented network of stakeholders and their expertise and concerted solutions.

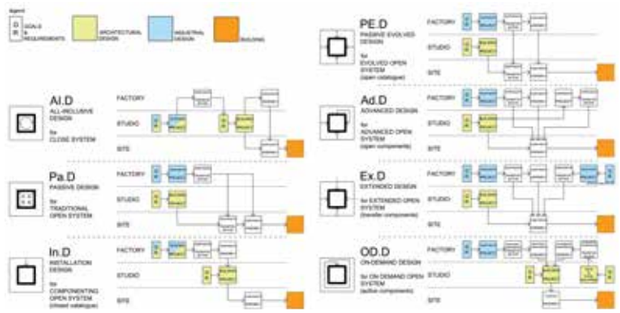

Fig. 2
The new proposal of design-centred classification for building process.

Inside new proposal for building system classification of process (Fig. 2), the thesis demonstrates that open on-demand high-industrialised technique can give suitable answers not only to contemporary living needs, but also, by nature, it can overcome some recurrent preclusions that have been making IBS difficult to increase and spread with satisfying results for housing buildings.

The outcome of the thesis is, among other, the guidelines and criteria (Fig. 3) to approach the design of a project in a resilient way and to lead it in a sustainable scenario.

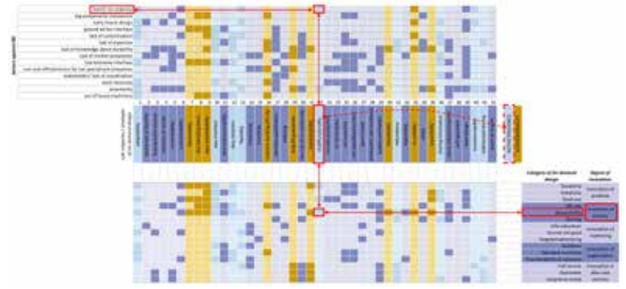

Fig. 3
Comprehensive matrix scheme of on-demand guidelines. From factors against IBS, crossed with sub-categories of on-demand design, some of which belonging to active-resilience (light blue) or sustainability (beige) requirements, crossed with fifteen category of on-demand design degree of innovation, belonging to the five degrees of innovation.

COMPLEXITY IN CONTEMPORARY ARCHITECTURE: THE INTERDEPENDENCE OF FORM AND SPACE

Amra Salihbegović – Supervisor: Domenico Giuseppe Chizzoniti – Tutor: Francesca Bonfante

The phenomenon of correlation between form and space can be traced in the design realm from the philosophical, aesthetic appreciation of form and space to diverse compositional implications in architectural design. Contemporary design implies even tighter dependences due to the rise of challenges in fulfilling all requirements, technological advancements, and socio-cultural demands. Indeed, the problem of contemporary architecture is that it doesn't follow inherited aesthetic rules governed by order, style, or geometry. It represents a field of diverse individual design attitudes that cope with current tendencies and evolve from complex preconditions of rapid development, strict construction rules, massive production, and transient needs, that retransform the design proposal by even abolishing the aesthetic and qualitative aspects. Particularly, if we consider contemporary tendencies of the supremacy of form in architecture, where contrary to a comprehensive design approach, formalism takes over.

New theoretical discussions leave out especially form as it mainly invokes a negative connotation in terms of one-sided or superficial analysis, that regards geometric features or concentrates on phenomenological, or aesthetic concerns. Therefore, the research principally aims to trigger a discourse on the notions of form and space in contemporary architecture and provide a better understanding and reading of architecture. It questions: How do architects generate form? How to create new forms with all technological advancements, but maintain all conceptual, technical, and aesthetical aspects? What are the implications of the interdependence of form and space?

The underlying premise is to understand the implications this dichotomy has not only in the creative design process hence in the final building design. Precisely, in terms of its qualitative characteristics within the design process and the conceptual strategies that refer to the underlying design intention. The developed methodological framework considers all the compositional, spatial, phenomenological aspects that affect the architectural design as it links the architectural form as a constant from the design process towards the final built work. The research proposes a conceptual framework of contemporary tendencies and an aesthetic measurement tool to understand, evaluate, and analyze the built work. In order to clarify the underlying correlation of form and space in contemporary design in a wide scope of research, it was necessary to underpin the core aspects of the trajectories of a design process, from the level of complexity in the design process to the conceptual approaches of current design attitudes, and simultaneously from the built work towards individual concepts. The challenge of determining the levels of complexity in this interdependence exists because the form space relation exists in the physical world, while the meaning responds to the creative intention of embodying a meaning and the connotation it has in individual experience.

Three examined themes of the form space dichotomy are the contemporary architectural expression analyzed through the concept of mask and mimesis, heterotopias of space in the aporetic and aleatoric design, and the aesthetic experience considering the concept of estrangement and unity. Contemporary architectural expression and its double articulation deal with the immaterial aspects of the building design, precisely the symbolic and iconological value through two distinct conceptual approaches that relate to the visual appearance in different manners.

The concept of mask refers to an imaginative representation of the architectural enclosure with multivalent qualities of the figure, while mimesis resembles a symbolic idea or imitation of already known qualities.

Heterotopias in contemporary architecture explores the new spatial qualities that emerged due to the needs and requirements of contemporary society. These new spatial qualities are showcased in the examples of two conceptual approaches the aleatoric design denoted by transformability and adaptability, whereas the concept of aporia refers to an architectural paradox of the correlation of form and space.

Contemporary aesthetic experience focuses on the importance of experiential richness and fulfillment of substantial and variable human needs. It inspects the correlation between architecture and the end-user through the concept of estrangement and unity in contemporary design, where the aesthetic experience represents the essence of the architectural work. The concept of estrangement refers to an alienation of the architectural work in its totality, while the concept of unity denotes a unified architectural composition.

The proposed tripartite assessment of the formal and spatial logic aims to decipher the aesthetic ideal from a qualitative point of view and to reveal the reasoning behind the design approach, representing in that sense a link between the evaluation of the built design and the clarification of the conceptual design intention in the initial design process. Formative ideas and design characteristics that emerged out of the analysis of several precedents can be used as a tool to generate the architectural form and an indication of a design approach.

Ultimately, this research does not offer definite answers but aims to unfold and integrate the discourse on the form and space interdependence, as the fundamentals of the discipline, into contemporary architecture.

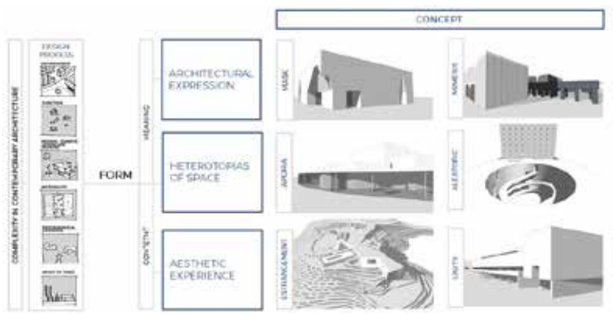

Fig. 1
Complexity in contemporary architecture: from design process to a conceptual approach

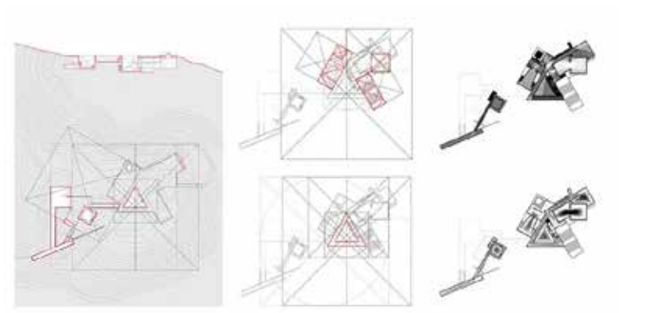

Fig. 2
Tripartite aesthetic measure –– case study analysis, Chichu Art Museum, Tadao Ando

DISCRETE MODELS AND SOLID MECHANICS OF BRITTLE MATERIALS

Vito Tateo – Supervisor: Siro Casolo – Tutor: Marco Scaioni

This research developed a plane rigid body spring model (RBSM) to deal with damage and crack propagation problems in isotropic and orthotropic brittle materials.
The RBSMs belong to the family of the discrete computational methods. They are based on the idea of discretizing a solid in particles of a certain shape and interacting among them according to specific rules. Thanks to an algebraic formulation they have been widely applied to the study of failure problems in brittle materials, that are characterized by the rapid spread of cracks as soon as the elastic limit is reached. Common downsides are an intrinsic failure anisotropy and limitations on the Poisson's ratios, that are related to the intrinsic micro-structure of the interactions of the discrete model.
The proposed RBSM was developed from the one presented by Casolo in 2004. The fundamental unit of the original RBSM is characterized by quadrilateral rigid elements connected to the beside ones by normal and shear springs. This RBSM is characterized by a simple mechanistic structure, that has allowed, its application also to the study of the compression response of a completely fractured tempered glass bonded to an ionoplastic interlayer.
The fundamental idea of the here proposed RBSM is the addiction of an interaction also between the elements that share only one node, that are the elements on the diagonals for quadrilateral rigid elements. Adding a diagonal spring that connects the element centers of gravity, this RBSM is able to model isotropic materials with a Poisson's ratio between -1 and 1/3, differently from the original model that shows an anisotropic response for materials with a Poisson's ratio different from 0. Furthermore, in the new model the mechanistic model structure is preserved, being the diagonal spring modulus proportional to the Poisson's ratio.
The addition of the diagonal springs, introducing also a new direction in which the failure criterion is checked, reduces significantly the failure anisotropy. This is further reduced defining a coupled failure criterion that couples the responses of the normal and shear springs. The capability of the model was proven by reproducing the experimental results for crack propagation problems on concrete notched beams. Both pure mode I and mixed mode crack propagation problems were successfully reproduced, getting also the concrete size effect. The analyses have been conducted comparing different solving algorithms looking for an efficient one that avoids convergence issues.
The Casolo's RBSM was widely applied to the study of orhtotropic materials, like masonry, taking also into account its texture at the macro-scale defining the model parameters in relation with an equivalent Cosserat continuum. Hence, in the end of this research, the capability of the new model of dealing with orthotropic Cauchy or Cosserat materials was investigated. Dealing with orthotropic Cauchy materials, the biggest challenge arises when the principal orthotropy directions are not aligned with the rigid element grid, because, in this case, a coupling between the axial and the shear responses arises, like in a generic anisotropic material. The study has showed that for square rigid elements the continuum equivalent to the RBSM has always the coupling terms equal for the two orthogonal directions. Anyway, some alternative approaches have been introduced to avoid this limitation, modifying the topology of the RBSM.
Comparing, instead, the RBSM with an orthotropic Cosserat continuum, the model topology and the kinematic of the springs impose that the coupling term between the shear responses has to be equal to the coupling term between the axial responses. Despite these limits, some possible strategies, to reasonably control the committed approximations, have been introduced.
In conclusion, this study has allowed to extend the range of applicability of a plane quadrilateral RBSM, characterized by a simple mechanistic topology. The good results obtained, both for the elastic and the crack propagation problems, despite the limited number of springs, in comparison to other discrete approaches, prove the power of the proposed model to study failure problems with a limited computational effort. In the end, the application to micro-structured materials offers a wide field for future developments.

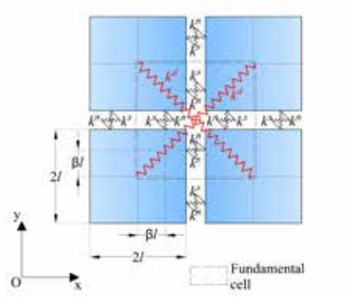

Fig. 1
Fundamental cell of the RBSM with diagonal springs

THE STRUCTURAL CHARACTERISTICS OF THE HOUSES OF THE KASBAH OF ALGIERS (TESTS AND SIMULATIONS)

Mohamed Amine Zouaoui – Supervisors: Antonio Capsoni, Boualem Djebri – Tutor: Marco Vincenzo Valente

The work is the result of a joint PhD thesis, developed under the guidance of bothe the Ecole Polytechnique d'Architecture ed d'Urbanisme (Algeria) and the Politecnico di Milano.

The organization of traditional urban fabrics into aggregates is one of the main characteristics of vernacular architectures, such as the Kasbah of Algiers, which underwent an almost total reconstruction after the 1716 earthquake.

Beyond the macrostructure configuration of the houses, various empirical and preventive techniques were used to reduce the seismic vulnerability of the houses, whose effectiveness remains undemonstrated on a scientific base.

Through multidisciplinary research, we study the structural characteristics of the houses of the Kasbah of Algiers built in the form of a compact aggregate category.
We proceed with a mechanical characterization of historic building materials followed by a series of static and seismic Finite Element structural Analyzes at different scales. A historiographical, methodological and operational contribution is proposed in order to restore the image of the historic center and ensure its sustainability. For this, we propose a complete and multidisciplinary methodological process of a structural rehabilitation project of an authentic aggregate from in-situ 3D scanning to the proposal for structural intervention.

First, an urban analysis highlights three distinct categories of aggregates, allowing the selection of a representative case study. The latter is the subject of a series of technical surveys including the application of 3D lasergrammetry allowing 188 scans to be obtained. The generated point cloud is an essential reference during the 3D modeling process based on the ten Grades of Generation and on a series of software based on BIM and NURBS.

In addition, mechanical characterization through destructive, semi-destructive and non-destructive tests is carried out on samples of historical terracotta bricks, lime and clay mortar and Thuja logs. This step reveals mechanical properties higher than those suggested in the literature and enriches the database of the properties of building materials for houses in the Kasbah of Algiers.

Parameterized Finite Element Modeling FEM is therefore carried out thanks to the HBIM model obtained with a high degree of accuracy as well as the mechanical characteristics of building materials. Different analyzes are undertaken including Static Linear Analysis LSA, Modal Analysis MA and Pushover Analysis PA, considering different configurations of the aggregate: with and without rigid horizontal diaphragms; in the aggregate and disaggregated state. The results clearly demonstrate a better structural response of the aggregate at the aggregated state rather than the disaggregated one, highlighting several local collapse mechanisms. These are the subject of a targeted structural upgrade proposal in order to improve the structural performance of this category of aggregate and consequently reduce its seismic vulnerability.

Three distinct strategies are proposed in accordance with the recommendations of international restoration charters as well as those resulting from the various structural numerical simulations.

The tie rod system is chosen as the most advantageous technique and is the subject of another post-intervention seismic structural analysis. The latter demonstrates a considerable reduction in the seismic vulnerability of the aggregate in all directions.

The structural rehabilitation project constituting a complete guide for vernacular architectures, is completed by a reference catalog of the local collapse mechanisms of compact type aggregates.