Sustainable Engineering for Resilient Built and Natural Environments

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Abstract We discuss the research that is being carried out at the Department of Civil and Building Engineering and Architecture (*Dipartimento di Ingegneria Civile, Edile e Architettura, DICEA*) of the *Università Politecnica delle Marche (UNIVPM).* Over the years the DICEA has steadily focused its attention on resilient environments and buildings, making a growing know-how and skill available to the local and broad communities. Pivotal to this have been dedicated projects and funds, like the UNIVPM strategic projects and the MIUR *Dipartimenti di Eccellenza* award. In conjunction with the four companion papers, produced by researchers of the four divisions of DICEA, we illustrate the DICEA's trajectory in the analysis of sustainable engineering for resilient built and natural environments.

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1 The Research Experience at Department of Civil and Building Engineering and Architecture

The Department of Civil and Building Engineering and Architecture (*Dipartimento di Ingegneria Civile, Edile e Architettura, DICEA*) is the reference Department of UNIVPM for the disciplines of Civil Engineering and Architecture. It is made of 4 divisions, 9 laboratories and 2 research centers.

1.1 The Architecture Division

The Architecture Division includes the disciplines of Architectural Analysis, Design and Restoration, operating in the field of Digital Cultural Heritage (DCH), History of Architecture and Geomatics, as well as Architectural and Urban Design. Researches deal with recycle and reuse of historical and modern building and spaces, through digitization and programmatic and sustainable upgrade, experimenting new models towards smart cities, heritage and buildings. Robust skills in DCH, history of architecture [2], geomatics were established through survey campaigns and studies about tangible and architectural heritage, with particular regard to the improvement of relevant tools for sustainable territorial development, based on knowledge, exploitation and regeneration of Cultural Heritage (CH) as a whole. The team developed researches in 3D acquisition (point cloud and image processing), modelling and semantic segmentation, Digital Libraries (DL) and Heritage Building Information Modeling (HBIM) [25, 40], Virtual Reality (VR) and Augmented Reality (AR) solution development and so on. Significant projects (Cultural evolved district, DCE, Marche region) allowed to validate methods in order to the stimulate the potential of DCH for creative industries, developing the territorial identity and promoting cultural tourism [20]. The team is also well connected with stakeholders (local/national authorities): the CIVITAS project shows a collaboration with the Galleria Nazionale delle Marche, the main museum of the Region. In the EU framework, the Division partner of the REMEMBER project (Interreg IT-HR) and of European COST Action, CYBERPARKS - Fostering knowledge about the relationship between Information and Communication Technologies and Public Spaces, dealing with strategies to improve CH use and attractiveness [31, 36]. Very high-level collaborations in landscape management and precision farming field are moving on [37].

From an historic point of view [3], research lines in the light of urban renewal and resilience were carried out in Inland areas damaged by earthquakes (Amandola historic center, Marche region). Other research areas are: urban and territorial analyses [9], strategic visions and scenarios for the enhancement of territorial areas [8], enhancement of historical contexts both for tourists and local communities, regional branding. Furthermore, the Division offers a transversal experience in architecture, urban planning and landscaping, such as contextual analysis, strategies for the enhancement of the territory of its historical contexts [4], architectural and

urban regeneration both for the reconstruction of local communities and for development for tourism purposes. The team members developed different experiences as heads of scientific research units funded in the areas of enhancement of physical and environmental heritage both in Italy and abroad. Particularly significant are: the regeneration of the port areas along the Paranà river and the 5-year trans-disciplinary project "Regiobranding, Branding of urban-rural regions through the characteristics of the cultural landscape" [24].

1.2 The Construction Division

The Construction Division is made up of two main research groups – the Architectural Engineering group (AE) and the Design and Construction Management group (DCM) – and also includes research activities in the field of legal (collective and individual) work, occupational safety, liability and professional deontology, in the construction sector [47].

The AE group has a well-known expertise in researches dealing with the assessment, optimization and development of building envelope material and components, with improved hygrothermal, energy [22], mechanical [1], cost and durability performances, for the application in new or existing and historical buildings [33]. Results led to patents and collaborations with industrial partners. Recently, the AE group started working on the development of advanced assessment tools, especially focused on life-cycle performances and on occupants' behavior and needs [23]. This is due to the growing need for the building designer to choose among several solutions and construction technologies, having to assess their performance according to multiple, somehow conflicting, points of view. Furthermore, a recent research interest for the group deals with the relation between human behavior and built environment, leading to a "behavioral design" approach for increasing people's safety in architectural spaces [5] and improving building and components performance, e.g. from an energy point of view. The rationale behind these researches is related to the need of making future buildings and components able to more and more adapt and respond to the users' needs in terms of comfort and safety, by also considering economic and environmental issues in the building life-cycle.

The DCM research concerns the development of new digital technologies to implement lean management principles in construction. The research encompasses the overall field of Automation in Construction, including Building Information Modelling (BIM), field automation, and building intelligence. The construction management group has a long tradition of research on these themes. Field automation for real-time construction management has been largely investigated. Advanced systems for the real-time tracking of workers' and equipment for real-time safety assessment and construction progress estimation have been developed [15, 34, 35]. Facility management research concerns the implementation of intelligent technologies for multicriteria probabilistic assessment of KPIs in large real estate management surveys [16] and the application of mixed reality technologies to onsite operation support.

Building intelligence has also been largely investigated, through large-scale projects (the SEAM4US FP7 EU Project) regarding the intelligent energy control of a metro station in Barcelona [46], stochastic modelling of occupants, and reduced order modelling methodologies for robust energy consumption forecasting [39].

1.3 The Infrastructure Division

The Infrastructure Division does research for the design and management of hydraulic infrastructures and for the analysis of environmental impact and risk (Fluid Mechanics, Hydraulics) and on the themes of the transportation infrastructures with attention to sustainability environmental protection of road and airport pavement structures.

The Transportation Infrastructures group holds a leading position in the research activities related to sustainable and innovative materials and systems for pavement construction and rehabilitation. It has a long tradition of research on the mechanical behaviour of pavement interlayer systems, which led to the development of a standard testing equipment for measuring the interlayer shear properties of bituminous pavements. Pavement interlayer reinforcement has been largely investigated leading to substantial improvement in pavement grids and composite technologies. The group is also well recognized in the scientific community for its cutting-edge research activity related to low-energy and sustainable pavements. The main research topics are related to asphalt recycling, warm mixes and cold paving technologies, as well as mechanical characterization of bituminous materials. The main research topics are related to the three-dimensional viscoelastic behaviour [28], the fatigue and healing phenomena [12]. The Transportation Infrastructures group has long-lasting scientific collaborations and students exchange projects with several international research institutions and Universities. The members of the group currently hold leading position in international research groups within the RILEM organization [11] and participate in large research projects focusing on pavement recycling (the CRABforOERE project) and on environmental sustainability of marine and air transport services (the ADRIGREEN project).

Much of the research by the Hydraulics group of the Infrastructure Division focuses on coastal, riverine and urban flooding and climate changes. With the specific purpose to investigate coastal flooding, the wave runup and inundation over sandy beaches, typical of the Italian coasts, have been studied using a Nonlinear Shallow Water Equations (NSWE) approach [43]. Further, to better understand the main causes of coastal inundation, the hydrodynamics induced by traditional rubble-mound breakwaters and innovative coastal protection structures have been inspected [38]. Riverine and urban floods have been analyzed by means of field experiments and numerical tests. Specifically, summertime and wintertime field campaigns have been carried out at the Misa River estuary (Senigallia, Marche Region), to investigate the seasonal variability of the interplay between sea and river forcing actions at an estuary characterized by cohesive sediments. The dynamics evolving during storms lead to high-flow conditions in the river, which potentially lead to sediment

removal off to sea and floods in the surrounding of the river mouth, including the urban area of Senigallia [10]. Such urban flooding has occurred in the recent years, causing large damages and deaths. Fundamental to the understanding of any type of floods is the analysis of the rainfall. That occurred in the Marche Region, has been inspected to find significant trends in the observed data, even in the perspective of climatic changes. The maximum annual rainfalls have been analyzed, using time-series longer than 50-years [44].

1.4 The Structures Division

The Structures Division is well-known for the long-lasting and solid research activity in several fields of structural engineering, characterized by the integration of a theoretical approach to engineering problems with a more experimental and application-oriented point of view. The main research topics are: mechanics of materials, structural modelling of buildings, computational mechanics, dynamics of structures, vulnerability and seismic assessment of structures and infrastructures, dynamic interaction between soil and foundation-structure, reliability of structures, analysis and control of bridges, innovative seismic protection techniques, dynamic identification and monitoring of structures. Research on mechanics of materials and structures concerns the theoretical aspect of electromechanical interactions in materials. Among the various topics are the mechanics of piezoelectric and ferroelectrics, the photoelasticity of anisotropic crystals and the propagation of electric charge carriers in scintillators [21]. A second main research topic regards multi-layer complex structures and laminates, analyzing the non-trivial interface conditions between the constituents of the composite [42]. The research concerned with the dynamics of structures investigates the nonlinear dynamics of cables, beams and composites loaded by time-dependent excitations and laid on spring beds and with different boundary conditions. Dynamical integrity has been largely studied as well, by determining the properties and dimensions of basins of attraction of structural systems. In the study of the seismic hazard of masonry structures, the so-called Non-smooth Contact Dynamics Method has been used, taking into account sliding and impacts between blocks [32]. The dynamics structural health monitoring has also been deeply investigated [30]. Regarding bridges, advanced models for box- and twin-girder steel-concrete composite continuous decks have been developed accounting for different features, such as, for example, the connection deformability [26]. Models have been used to analyze composite girders with internal and external prestressing systems and to investigate construction aspects such as fractionated casting of the slab. Moreover, the research on bridges has been focused on the soil-structure interaction effects [17], on seismic isolation systems and on structural monitoring techniques, under static and dynamic loads. Regarding buildings, the research activities have included the seismic protection through dissipative internal or external systems; in addition to advanced numerical simulations, experimental investigation on structural elements, mock-up and real structures have been performed [27] and tests for the dynamic

identification and for continuous structural monitoring have performed. Experimental investigations have been also carried out on historic and modern masonry walls and on reinforced concrete elements strengthened with carbon FRP [13, 14].

2 The 2017 Departments of Excellence Award Experience

In 2017 the Italian Minister of Instruction, University and Research (MIUR) opened a call named "Dipartimenti di Eccellenza" (Departments of Excellence) aimed at awarding the best 180 Departments in the Italian Universities (according to the Law 232/2016). The call was managed in two steps. In the first one the best Departments were selected based on the results of the previous Italian Departments assessment done by the National authority (ANVUR). After this first stage the DICEA ranked first with the score of 100 point out of 100. Thus, the Department was admitted to the second stage, where the submission of a specific 5-years project for the Department's development was required, including objectives, strategies and implementation plans. The deadline was 17 October 2017. The Department's council established a dedicated committee to define the research topics and to prepare the application. It was realized that the development of a resilient built and natural environment through a sustainable engineering effort was, from the one side, a topic of major social interest and, from the other side, a topic where the various Department's divisions would have been able to provide innovative, interdisciplinary and coordinated research advances. The project was submitted, and DICEA was one of the 14 selected and awarded in the field of Civil Engineering and Architecture.

The research approach to sustainable engineering for resilient environments addresses the fundamental issues of resilience and sustainability by developing a coordinated methodological perspective among the various research groups and a technological framework to tackle them in a combined and optimized way. Three research lines, encompassing extremely wide fields of the civil and building engineering and architecture research, have been identified as the driving perspectives of the future research at DICEA:

- Environmental Resilience and Risk Mitigation, encompassing resilient infrastructures, environment protection and safety-oriented structural design.
- Advanced digital technologies for smart facilities, life cycle engineering, lean design and construction management.
- Digital cultural heritage for landscape protection and fruition.

3 Environmental Resilience and Risk Mitigation

This section briefly introduces the four companion papers, which detail further the research themes outlined in the previous section, so as to provide a self-contained overview of the Department research. The first section introduces the themes of

the digital revolution in construction and the second discusses aspects of cultural heritage preservation. The last two sections describe papers addressing the research in the structure and infrastructure domains.

3.1 Cultural Heritage and Landscape: Digitization, Analysis and Design Aiming at a Resilient Future

The research activities about cultural and built heritage at various scales, from architecture to landscape, highlight how innovative analysis and design approaches can challenge the current methods and pursue the main scope of increasing heritage resilience.

Major results and findings in several disciplines, such as history of architecture, geomatics, drawing and survey, restoration, regeneration and design, are discussed throughout a set of case studies. These allowed to develop tools to perform rapid surveys and multilevel readings (stylistic, structural, historical, behavioral, etc.) as well as robust procedures for interventions and recycle of built heritage. The main idea is to highlight overlapping and consonances of different approaches although each discipline intends in a specific way the heritage: ranging from heritage as motor of development, as digital cultural innovation, as identity, as experienced landscape to heritage as conservation.

The Cultural and Built Heritage collection, conservation and access in novel, accessible and attractive ways demand for digitizing museums and archaeological/historical sites, as well as for designing methodologies to represent, manage and exploit cultural heritage data at different levels, ranging from 3D/4D models to domain specific e.g., architectural, historical, etc. The generation of virtual "facsimiles" of artworks, monuments and architectures can unify their scattered elements, enables public access to inaccessible places and visitors to interact with perishable objects, promotes the preservation of fragile sites and simulates damaged or lost objects. The availability of semantically enriched data enables smart applications for fruition, preservation and study of DCH collections. This development has the potential both to collect and disseminate the cultural heritage in an effective and low-cost mode and to implement a key strategy to increase cross-curricular skills. In particular, the sustainable valorization and resilient management of CH require effective participatory (i.e. multi-level and multi-stakeholder) governance and enhanced cross-sectoral cooperation.

The relationships between history and project, between project and city and between heritage and contemporaneity are the centers of the research action, dedicated to the regeneration of the existing heritage. Actions able to develop methods of intervention in the relationship between heritage and recent context, the result of plural stratifications occurred in an extended time that includes more stories, a time far away to cure, but also a close time, that modernity that produced a large heritage to be recovered. The idea of conservation should therefore give way to more flexible

readings and uses where "conservation and modernity are not opposites" (Koolhaas) and where creativity and design are for the recovery of heritage, an instrument of thought and invention architectural. This calls for an idea of urban regeneration specific, anchored to places, and oriented towards the construction of socio-cultural networks to trigger a process of transformation involving all actors and bringing design ideas closer to needs.

Finally, the studies try to extend the validated approaches to similar cases in the heritage field. The main research activities, indeed, entail the definition of the fundamental paradigms of resilience for heritage and landscape, against the backdrop of the contemporary techno-cultural revolution.

3.2 Rethinking Buildings Design, Construction and Management Through Sustainable Technologies and Digitization

A technological development not threatening natural and human life is one of the core concepts of sustainability. In the construction sector, which is worldwide responsible of a huge consumption of energy and natural resources, thus strongly impacting on climate change, sustainability means the need of a prompt transition towards eco-friendly, smart and resilient buildings. However, despite the current Fourth Industrial Revolution, where many sectors have been able to transform themselves improving productivity while lowering the impact, construction is still suffering from several intrinsic weaknesses. The research in the Construction Division investigates new approaches based on technology innovation and digitalization, aiming to develop and optimise innovative, durable and sustainable solutions for buildings and construction processes and management. This outlines the emerging challenges and future directions of the research at the DICEA of the UNIVPM in this long-established sector. Several research trends are identified for a more sustainable and resilient "Construction 4.0". Firstly, the development of building technologies aims to integrate, in a logic of constructive simplification, multiple aspects and functions (e.g. energy efficiency, seismic resistance and high durability), reducing environmental impacts, costs and construction time. It also includes the development of "cognitive" technologies, able to adapt and respond to the users' needs, involving several performance domains (e.g. energy, comfort, safety, durability). Then, future research also focuses on the development of effective building design and management tools, able to address in an efficient way all the complex set of design, performance, environmental and economic issues. Finally, future study trend will also involve the development of a real-time construction management approach, supported by pervasive sensing and on-site site intelligence, and the development of digitization of design and construction processes, in order to optimize these processes.

3.3 Research and Engineering for Resilient Infrastructures and Environment Protection

The Transportation Infrastructures group has been involved in research activities focused on the development of sustainable materials and systems for resilient transportation infrastructures, and organized the interlaboratory experiment "Advanced Interface Testing of Geogrids in Asphalt Pavements", promoted by the RILEM, to verify the effectiveness of pavement grid in improving the repeated loading resistance and for preventing or delaying reflective cracking. The *pavement reinforcement* by grid installation at the interface of structural layers has been studied through both full-scale applications and laboratory investigations. Within *cold recycling,* the group investigated the short- and long-term mechanical behaviour of the cold-recycled mixtures (CRM). Modelling has been carried out to analyse the evolutive behaviour of CRM and the combined effects of bituminous and cementitious binders on their mechanical response. Laboratory characterization was then related to performance monitoring of a full-scale test pavement to optimize the prediction of the stiffness properties of CRM layers over time [29]. Recent research efforts focused on the innovative technology of *Warm Mix Asphalt (WMA)*, aimed at significantly reducing the production temperature of bituminous mixtures without compromising their mechanical properties. The potential benefits deriving from the combination of WMA and recycling techniques have been also investigated [45]. Further important research topics have concerned *photocatalytic techniques* to de-pollute atmosphere from traffic emissions [7] and the *use of waste materials* (e.g. C&D material, rubber from reclaimed tires) for road applications.

Future research activities of the Transportation Infrastructures group will focus on the development of technical solutions for resilient transportation infrastructures according to environmental and economical sustainability. The acquisition of new testing equipment will increase the potential of the laboratory aimed at the advanced rheological characterization of recycled and low energy materials (through cold and warm technology) and the development of innovative solution for resilient pavements (e.g. reinforced pavements, low noise pavement and self-healing materials).

The group of Hydraulics focuses on themes related to both resilient infrastructures and environment protection. The riverine and estuarine environments have been studied through a series of field campaigns, funded by international institutions (e.g., the Office of Naval Research—Global), to inspect the interplay between river and sea forcing actions in micro-tidal environments of different kinds, like the Misa River estuary (Senigallia, Italy), typical of the Mediterranean area [10]. Such studies underline that riverine and sea forcing significantly affect the mixing and transport of nutrients and pollutants from the river to the sea. Furthermore, inspired by the Misa River flood recently occurred in Senigallia (Marche Region, Italy), numerical modelling has been undertaken with the aim to both characterize the hydrodynamics during the urban flood and analyze the consequent pedestrians' evacuation [6]. With reference to the coastal environment, studies of both numerical and laboratory nature have been carried out. Many of them where related to the development and application of an

in-house solver based on the Nonlinear Shallow Water Equations. This has been used for multiple purposes, including the analysis of: the wave propagation in protected coastal areas and following vorticity generation and propagation due to low-crested structures, the seabed erosion in either free-from-obstacle or protected beaches. Another important topic of research is the prediction and analysis of snow avalanches impacting into lakes, with the following generation of impulse waves [48]. Such phenomenon led to many important problems in mountainous areas, hence the prediction of the generated wave may provide important information for both risk assessment, design of suitable warning systems, protective civil engineering works, etc.

Active research is ongoing on the following topics:

1. modelling of river floods, turbulent flow structures, nearbed sediment transport, river bed morphology evolution;
2. prediction of the coastal inundation due to sea storms on real beaches; modelling of fluid-structure interactions and flows of interest for biological applications.

3.4 An Overview of the Structural Safety-Oriented Research in the Region Marche Seismic Area

In the last decades, Italy's central regions, including Marche, have been affected by several earthquakes, causing the partial or total destruction of masonry and reinforced concrete (RC) buildings. The seismic events have severely damaged ordinary constructions, structures of strategical importance, and historical and monumental buildings (e.g., churches, monasteries, towers). This has caused dramatic consequences within the urban fabric and inhabitant communities, confirming once more the high seismic vulnerability of the Italian existing RC and masonry constructions and the need of enhancing the mean safety level of the population. The importance of the prevention during these calamitous events has highlighted the urge of studying the dynamical behavior of structures in order to better understand their response under seismic actions, assess precise criteria of vulnerability and develop suitable protection measures against earthquakes, improving the structural capacity. The dynamic analysis and the seismic structural safety can be considered two of the most important research topics of the Structural Division. The researches can be gathered into the four main areas.

1. *New methods of modeling the dynamic behavior of structures*. The adequate modeling of the dynamic behavior of RC and masonry structures is needed for the assessment of safety and damage levels, the maintenance and the structural upgrading possibility. The researches have focused on the study of the global response of RC and regular and non-regular masonry buildings by means of dynamical linear and nonlinear analyses using bar-frame models with lumped or diffused plasticity. To investigate the mechanical behavior of structures, such as

masonry building, discrete element techniques have been developed in order to have a better knowledge of the collapse mechanisms [18].

2. *Vulnerability assessment of existing structures*. The evaluation of the seismic vulnerability of existing buildings has a key role in determining and reducing the impact of an earthquake. With reference to old RC and industrial precast structures, the research activities have focused on the experimental identification of some typological aspects that often characterize these buildings and the analysis of their behavior through nonlinear models. Masonry buildings, lacking an adequate lateral resistance and ductility, have been analyzed by means of sophisticated methods in order to asses or predict the seismic behavior and/or the expected damage [19].
3. *Experimental studies and advanced techniques of seismic retrofitting*. The researches have focused on the development of innovative dissipative braces (viscous, visco-elastic, elasto-plastic dissipative devices), in order to enhance the seismic structural performance, and on advanced techniques of strengthening through the use of near surface mounted fiber reinforced polymers (FRPs) [13].
4. *New prospects for safety*. In this field, several research activities are in progress aimed at studying efficient structural health monitoring systems, providing information about the modal parameters evolution of structures and infrastructures, which are often used for the calibration of structural models for the seismic vulnerability assessment or the retrofit design [30, 41]. Moreover, the researches have focused on the seismic isolation by means of High Damping Natural Rubber bearings, which represents a recognized technology able to protect efficiently structural and non-structural components and equipment.

4 Conclusions

We have introduced the research that is being carried out at the *Dipartimento di Ingegneria Civile, Edile e Architettura* of the *Università Politecnica delle Marche* towards the achievement of environments and buildings resilient to natural disasters, like earthquakes and floods, and the development of methods and techniques for a sustainable engineering as a fundamental tool for the circular economy. We have referenced the past research that has been carried out over the years at DICEA, steadily focused on resilient environments and buildings, and the pivotal experience of the strategic projects award gained from the MIUR *Dipartimenti d'Eccellenza* competition. We have then illustrated the DICEA's current trajectory in the analysis of sustainable engineering for resilient built and natural environments. Finally, we have briefly introduced the four companion papers produced by researchers of the four divisions of DICEA. A thorough bibliography of the Department research is provided.

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