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EARTHQUAKE PROTECTION OF MASONRY HISTORICAL CONSTRUCTIONS: OVERVIEW OF RESULTS FROM NIKER AND PERPETUATE EUROPEAN PROJECTS

Claudio Modena[1], Sergio Lagomarsino[2], Francesca da Porto[3], Serena Cattari[4]

ABSTRACT

Potential damages on Cultural Heritage (CH) assets are currently too high, mostly due to their intrinsic vulnerability, and to the fact that most of the technologies applied to date are too intrusive, cost-inefficient, and often unreliable and/or non-effective. As so, the need to develop proper strategies to mitigate the risk associated with seismic vulnerability is unquestionable.
The Commission of the European Communities has recently funded two research projects: NIKER, which aims at developing an integrated methodology for the systemic improvement of the seismic behaviour of CH assets; PERPETUATE, which aims at developing a displacement-based procedure for the vulnerability assessment and the design of interventions of historical masonry buildings.
In the present contribution, an overview of the main objectives and steps of the two projects is given.

Keywords: *Architectural heritage, Masonry, Seismic assessment*

1. INTRODUCTION

The damage assessment to historical masonry buildings after past and recent earthquakes has shown their high seismic vulnerability. L'Aquila earthquake, 2009 in Italy, severely struck a large number of monumental buildings, such as churches, towers, palaces and ancient urban aggregates: this confirms the need of proper procedure for the preservation of cultural heritage in seismic prone areas. Differently from the case of ordinary buildings, concepts related to the protection of the cultural heritage should be added to requirements strictly associated to the safety of people and to operational and economic aspects: thus, all these aspects should be considered in an integrated approach. The possibilities of nowadays technologies, in terms of materials, processes, design tools, etc, for mitigating the risk associated with seismic vulnerability of CH assets are unquestionable. However, in contrast to the expectations, some defects that make useless the effects of the interventions and even increase the vulnerability of CH assets can arise for various reasons, such as:

- The use of inadequate materials that give rise to chemical, physical and mechanical incompatibility with the existing ones;
- The use of inadequate intervention techniques that alter significantly the original bearing system of the structure and/or are based on concepts that were proven to be reliable in case of modern structures and are applied (without prior validation) to historic structures as well;
- The use of inadequate analyses of historic structures. The problems arising here are related to analyses performed on the basis of limited information regarding the original structural system; the use of unsuitable analytical tools; the adoption of behaviour models developed for modern structures. Furthermore, very often, dated design methods are applied.

[1] Full Professor, University of Padova, Italy, claudio.modena@unipd.it
[2] Full Professor, University of Genoa, Italy, sergio.lagomarsino@unige.it
[3] Assistant Professor, University of Padova, Italy, francesca.daporto@unipd.it
[4] Assistant Professor, University of Genoa, Italy, serena.cattari@unige.it

Hence, on one hand, it is necessary to develop innovative materials and technologies that will ensures at once effectiveness, economic application and maintenance, low-intrusiveness towards the existing structure, respect of authenticity and of the original structural concept, and high structural performance and improvement of seismic behaviour. On the other hand, since the behaviour of masonry structures is strongly non linear, it is necessary that seismic assessment refers to proper analyses methods (both non linear static and dynamic), verification procedures (by favouring, according to all the recent research trends, a displacement-based approach rather than a force-based one) and modelling strategies. Indeed a reliable, and knowledge-based, seismic assessment represents a necessary step to guarantee the conservation of cultural heritage through an optimization of interventions. Despite all the above-mentioned issues, the great variability and complexity of masonry historical buildings makes difficult to propose well established approaches, as in codes for the case of new buildings, to be adopted as reference.

The effort for preservation of historical constructions is nowadays shared by numerous countries at international level. The relevance of this topic is also testified by the 7th Framework Programme of the European Commission, which involves in theme 6 *Environment* a specific topic *Assessment and conservation of cultural heritage* (Area 6.3.2.1). In particular two projects, NIKER (www.niker.eu) and PERPETUATE (www.perpetuate.eu), have been funded.

NIKER project (New Integrated Knowledge-based approaches to the protection of cultural heritage from Earthquake-induced Risk)involves a consortium[5] of 18 partners, which includes 9 Universities, 2 Research Centres, 1 Public Institution and 6 SMEs. 12 countries are represented, among which Italy, Germany, Czech Republic, Greece, Portugal, Spain, United Kingdom, and 5 International Cooperation or Associated Partner Country: Turkey, Morocco, Egypt, Israel, Bosnia and Herzegovina. The project aims at developing and validating innovative materials and technologies for systemic improvement of seismic behaviour of Cultural Heritage (CH) assets. These will be accomplished through the development of an integrated methodology, which includes also design methods and innovative monitoring & early warning techniques. The comprehensive methodology will be then included in guidelines for end users of the technologies and for owners and public bodies charged of the maintenance and management of CH buildings. The main steps, on which the research relies, are: 1) creation of a database of earthquake-induced failure mechanisms, construction types and materials, intervention and assessment techniques with a new relational structure, with the task of orienting and assisting the development of advanced materials and innovative techniques and developing new integrated methodologies with a systemic approach; 2) extensive experimental testing, numerical simulations and derivation of design methods for vertical and horizontal structural elements, for connections, and for the overall seismic behaviour of buildings, which form the core of the project; 3) development of knowledge-based assessment procedures, also through real case-study application of investigation and monitoring techniques, and final validation of the entire methodology, including its application on real case-studies. Further details on aims and structure of NIKER project may be found in [1].

PERPETUATE project (PERformance-based aPproach to Earthquake proTection of cUlturAl heriTage in European and mediterranean countries) involves a consortium[6] which includes 6 Universities, 2 Public Institutions and 3 SMEs. In particular, 5 European Countries (France, Greece, Italy, Slovenia, United Kingdom) and 1 International Cooperation Partner Country (Algeria) are represented. Final aim of the project is the development of European Guidelines for evaluation and mitigation of seismic risk to cultural heritage assets. In particular, the methodology proposed uses a

[5] University of Padova – Italy – Coordinator; Federal Institute for Materials Research and Testing, Germany); Institute Of Theoretical And Applied Mechanics, Czech Republic; National Technical University Athens, Greece; Politecnico di Milano, Italy; Universidade do Minho, Portugal; Universitat Politecnica de Catalunya, Spain; University of Bath, United Kingdom; Gazi University, Turkey; Ecole Nationaled' Architecture, Morocco; Cairo University, Egypt; Israel Antiques Authority, Israel; Bozza Legnami Srl, Italy; Cintec International Ltd, United Kingdom; Interprojekt d.o.o., Bosnia and Herzegovina; S&B Industrial Minerals S.A., Greece; ZRS Architekten Ingenieure Bürogemeinschaft, Germany; Monumenta Conservaçao e Restauro do Patrimonio Arquitectonico, Lda, Portugal.

[6] University of Genoa, Italy – Coordinator; ENEA (Italian National Agency for new technologies, energy and sustainable economic development), Italy; Bureau de recherches géologiques et minières (BRGM), France; Aristotle University of Thessaloniki, Greece; National Technical University of Athens, Greece; University of Ljubljana, Slovenia; University of Bath, UK; University of Sciences and Technology Houari Boumediene, Algeria; Building and Civil Engineering Institute (ZRMK), Slovenia; Il Cenacolo S.r.l., Italy; Proind S.r.l, Italy.

displacement-based approach for the vulnerability assessment and the design of interventions. It is based on the following fundamental steps: 1) definition of performance limit states, specific for the cultural heritage assets (considering both architectonic and artistic assets); 2) evaluation of the seismic hazard and of the soil-foundation interaction; 3) construction knowledge (historical analysis, survey, non-destructive testing, material parameters, structural identification); 4) development of structural models for the seismic analysis of masonry structures and artistic assets, in the actual state and for the design of interventions. Two main scales are considered: a) the assessment of a single historic building or artistic asset; b) the evaluation of the seismic risk to cultural heritage assets in a wide territorial area, in order to plan mitigation strategies. Further details on aims of PERPETUATE project may be found in [2].
Within this context, the paper aims to provide an overview on some of the results achieved by the two projects. The attention is focused on some of main steps of the seismic assessment path, that is: knowledge phase, modelling and analysis methods, design of strengthening interventions. In addition, the most relevant results on the experimental campaigns performed and the selected case studies are illustrated.

2. KNOWLEDGE PHASE

The seismic safety assessment of existing buildings is affected by more uncertainties than in the design of a new building; in fact, uncertainties related to the incomplete knowledge of the asset (epistemic uncertainties) add up to the statistical ones. In order to reduce these uncertainties, the knowledge phase represents a preliminary but fundamental step. In fact, all collected data orient subsequent phases of the seismic assessment, such as the choice on suitable modelling strategies to be adopted.
Knowledge phase includes several aspects such as historical analysis, in-situ investigations, material parameters characterization, and also monitoring techniques, that are useful for the identification of the dynamic properties of buildings, but also as a tool for model updating, early-warning, and verification of the effectiveness of interventions.

2.1. Cultural heritage classification

A proper classification of both architectonic and artistic assets represents one of the first steps to face the issue of the seismic assessment of CH assets. In fact, on the one hand, such classification allows to identify the more reliable mechanical models to be used in the description of the seismic response of the different types of buildings and artistic assets; on the other hand, it allows defining reliable damage variables related to each type of building and main elements of the construction.
To this aim, in PERPETUATE project, adamage and typological classification of cultural heritage asset have been proposed: this classification has to be considered as strictly "mechanical", since the occurrence of different types of damage are closely related to building morphology (architectural shape, dimensions) and technology (type of masonry, characteristics of horizontal diaphragms, effectiveness of wall-to-wall and floor-to-walls connections). Thus, starting from the identification of the most relevant macro-elements in historic buildings and of the corresponding damage types, seven architectonic asset classes have been identified [3], such as: *A* – assets subjected to prevailing in-plane damage (e.g. palaces, castles,...); *B* – assets subjected to prevailing out-of-plane damage (e.g. churches, mosques,…); *C* – slender assets that can be represented by a mono-dimensional masonry element (e.g. towers, minarets,…); *D* – arched structures subject to in-plane damage (e.g. triumphal arches, aqueducts, cloisters,...); *E* – massive structures in which local failure of masonry prevails (e.g. fortresses, city walls,..); *F* – blocky structures subjected to overturning and sliding (e.g. columns, archaeological ruins); *G* – aggregated buildings in the historical centres. In addition, three main classes for artistic assets have also been defined [3]: *P* – assets which are structural elements of the building (e.g. carved stone columns,…); *Q* – assets which are strictly connected to structural elements of the building (e.g. frescoes, mosaics, stuccoes, stone portals,…); *R* – assets which are independent elements, with their own seismic response (e.g. pinnacles, statues, balcony,…).

2.2. New structured catalogue

The first step of the NIKER project consisted of studying the available classifications and databases on earthquake induced failure mechanisms, construction types and materials, interventions and assessment techniques, in order to cross-correlate the information already available in the literature. On one hand, Cultural Heritage construction typologies (such as buildings and palaces, religious buildings, towers, free standing elements, etc.) and the related structural elements (such as walls, floors, roofs, arches and vaults, connections, etc.) are listed. The elements are further specified in terms of material and typology, and their properties and the source in the literature from which these have been gathered are also listed. On the other hand, a simplified list of most significant failure mechanism for each structural element is given. A sort of matrix, connecting the available intervention techniques with the elements on which they are applicable and the related failure mechanisms that can be hindered or reduced, is the main outcome of the catalogue. This relational structure also gives the performance indicators of the strengthening techniques, when these are available in the literature or from the tests that have been carried out within the project. This catalogue, whose structure has been defined and is being currently fed with data, will be available on-line by the end of the project [4].

2.3. Seismic damage mechanisms

In PERPETUATE project, varying the classes defined for both architectonic and artistic assets mentioned in §2.1, an abacus of different damage classes and subclasses, they may be attributed to, has been defined. Moreover, an innovative procedure for the identification and the collection of the seismic damage of cultural heritage assets collected in situ or by photographic observation (named LOG-IDEAH – *LOGic trees for Identification of Damage due to Earthquakes for Architectural Heritage*), has been developed [5]. It is based on the use of a decision logic tree: a support tool that uses models of decision and their possible outcomes to develop an automatic system trained for choosing between several courses of action.

2.4. Diagnostic techniques

As far as diagnostic techniques and inspections are concerned, the main techniques adopted within the NIKER project have been sonic pulse velocity, impulse radar, ambient dynamic testing, jack flat testing and thermovision, mainly in the framework of the case-studies that will be presented in section 5.1 [6]. Most of these techniques have been calibrated to be carried out before and after interventions, to assess the strengthening effectiveness. Thermovision has been also innovatively applied, in some cases, for the verification of the bonding condition of FRP strengthening. Dynamic identification tests have been of special importance for the updating and validation of structural models. Two dynamic testing systems have been used: one based on the measure of the acceleration at some selected points, and the second based on velocity parameters. Although these techniques are mostly oriented to a punctual NDT (or MDT) inspection, or give results directly related to the physical and structural parameters of the structure in the selected period of testing, they can also be used for monitoring purposes through a periodical or repeated application. A repeated or periodical use permits the identification of variations in the structure caused by increasing damage or possible interventions. The adequate application of this sort of monitoring requires a parallel implementation of continuous static monitoring of environmental conditions and structural parameters such as crack openings, which will be dealt with in section 5.1.

The use of several diagnostic techniques (including NDT,MDT and DT methodologies, radar interferometry and ambient vibration measurements), has been reviewed in PERPETUATE project: particular attention has been paid to their intrusiveness and effectiveness for the assessment of both architectonic and artistic assets. The reliability of different techniques has been also directly verified in situ through the application for many of the case studies selected (as listed in §6.2). Moreover, in case of CH, proper criteria to optimize the plan of investigations reveal to be essential. In fact, the application of the traditional approaches proposed in codes in case of ordinary existing buildings could significantly increase the "minimum" number of investigations/testing to be performed in order to reach a certain knowledge level: this could be inadmissible due to the need of guaranteeing the primary conservation objective. To this aim, an innovative procedure, based on the use of sensitivity analyses, have been developed oriented to: identify the parameters which significantly affect the structural response; optimize the plan of in-situ investigations and testing to minimize the invasiveness on heritage buildings; calibrate and more effectively address the use of confidence factors.

3. MODELLING AND ANALYSIS METHODS

The complexity of cultural heritage requires referring to various proper modelling strategies for each different architectonic asset types (such as churches, palaces, towers) and their prevailing seismic damage modes (e.g. if in plane or out-of-plane prevailing). Due to wide variety of materials, geometry, constructive details and real preservation state of CH, the choice of the most suitable modelling strategies to be adopted represents a very complex task. According to the performance-based approach (thus to safety verifications made in terms of displacement rather only of strength), they should be capable to describe the nonlinear behaviour of the assets up to their collapse (by allowing to perform both nonlinear static and dynamic analyses). Actually, the reliability of models in describing the actual behaviour and conditions of CH represents one of the most effective tools also to optimize the design of interventions.

3.1. Modelling strategies

Within the NIKER project, numerical modelling was carried out at two main levels. On one hand, complex numerical strategies were adopted to simulate the experimental tests that will be briefly summarized in section 4. On the basis of these complex models, parametric assessment has been carried out to define critical mechanical parameters, to highlight the performance of the proposed intervention techniques, and to assist the tasks of optimising design. These models have been also used to derive more simplified relationships to be applied in the analysis of entire structures. Hence, parametric study of buildings when varying their main features is being carried out. The behaviour of these structures under repeated shaking, to identify limit threshold associated with accumulated permanent deformation, is simulated. The role of performance-related overall properties, such as dissipation, ductility, monolithism, etc. and the building performance and response parameters to be used in seismic assessment and performance-based design are being identified.
In PERPETUATE project, the use of different modelling strategies as a function of various damage modes, asset types and scale of analysis considered (if that of the single asset or the territorial one) have been discussed. For territorial scale assessment, displacement-based vulnerability models have been distinguished if on empirical or analytical basis: criteria to select the “optimal” model to be used among those proposed in the literature to optimize the time consuming effort/assessment reliability ratio have been proposed. For assessment at scale of single building, models have been classified following two criteria: scale of discretization (whether material or structural element one) and constitutive modelling of masonry (whether continuous or discrete). Four types of models have been identified: 1) Continuum Constitutive Laws Models, 2) Structural Element Models (e.g. the equivalent frame approach), 3) Interface Models, 4) Macro-Blocks Models. In general terms, continuous models are particularly suitable to analyse the global response of buildings (mainly associated to the in-plane response of walls and to the activation of a box type behaviour) while discrete models are commonly used to describe local mechanisms (usually subjected to out-of-plane failures). Specific improvements on some models available in the literature [7-9] have been formulated and implemented to optimize their reliability in capturing specific characteristics of historical constructions.

3.2. Verification procedures

As known, Performance Based Assessment (PBA) usually considers a set of selected *Rehabilitation Objectives*, related to the fulfilment of some *Performance Levels* (PLs) corresponding to well defined Earthquake Hazard Levels. In case of CH, PLs have to be also linked to cultural relevance concepts: thus, the conservation of the cultural heritage asset and the safety of people should be considered in an integrated approach. To this aim, within PERPETUATE project, proper *Safety and Conservation Objectives* have been defined by adding to use and human life targets – usually considered also in case of ordinary buildings – the following aspects: *Building conservation* (the preservation from building damage is not related, as for ordinary buildings, to the costs of repair or rebuilding but to the possibility of restoration, due to the intangible value of a CH); *Artistic assets* conservation (in many cases, irreparable damage to artistic assets can occur also in the case of moderate damage to structural elements, thus it is necessary to define specific PLs).
As regard the analysis and safety verification methods, particular attention has been paid to non-linear static and dynamic procedures. Their application to analyse both global seismic response of the structure and local response of single parts is considered. Moreover also soil structure interaction and foundation problems are included in the analysis if relevant [8,9].
In case of nonlinear static analyses, an innovative procedure to define PLs on the capacity curvehas been proposed [10]. It is addressed to combine different criteria (either on heuristic basis and on a structural element approach) and take into account the different scales that concur to define the overall seismic response, like as: the scale of structural element (*local damage*), mechanisms in architectonic elements (*macroelement pushover curve*), global behaviour (*pushover curve of the whole building*).

4. EXPERIMENTAL TESTS ON AS-BUILT AND STRENGHTENED ELEMENTS

Different types of vertical elements exhibit a different response when exposed to the same loading scenario, in particular when it concerns dynamic loading. It is therefore of paramount importance to investigate the principal response of different masonry wall types and, from there, designing tailored strengthening techniques. However, not only the behaviour of masonry walls is of basic importance to understand the seismic behaviour of masonry buildings. Indeed, the typical horizontal elements such as timber floors and roofs and masonry vaults, have a crucial role in the seismic behaviour, as they are required to resist under lateral loads, to improve the global building behaviour through effective connection and to distribute the horizontal forces, when they have sufficient in-plane stiffness, to the shear walls. Lastly, the overall response of historic buildings is determined by the behaviour of the single structural elements, as well as by their mutual connections. However, testing of connections is rarely performed and very few codes of practice deal with it, and with the possible strengthening techniques to be adopted for improving their performance. Hence, it is necessary to gather information on the behavioural laws that govern the seismic response of vertical and horizontal structural elements and of their connections, to calibrate and develop adequate models and to improve the available strengthening techniques and the corresponding design practices. At this aim, there are a number of pseudo-static experimental testing procedures available, but it is also possible to carry out shaking table tests of model structures and structural sub-assemblages, to investigate the actual dynamic response, before and after strengthening.

4.1. Tests on masonry panels

The tests on masonry specimens within the NIKER project were carried out on stone, brick, earthen, and timber-framed masonry walls. The construction techniques for stone masonry consisted essentially in regular and irregular three-leaf limestone masonry, strengthened with various types of natural hydraulic based grouts. Tests were also carried out on real walls on-site. Adobe wall specimens were constructed as one-leaf masonry with earthen mortar. Earth blocks consisted of mechanically molded adobe. Rammed earth specimens were prepared in the traditional way, by hand with formwork. Cob specimens consisted of a mixture of raw earth and straw and were cut from a larger block. These types of masonry walls were strengthened by means of lime based grouting material with pozzolanic additions and textile belts. Adobe walls, together with one leaf clay brick masonry walls, were also tested before and after applying reinforcing systems made of steel wire ropes or geonets fastened to both wall façades. The timber-framed panels consisted of timber and claybrick masonry. Different types of reinforcement were considered, namely steel bolts and steel plates. The static and cyclic tests carried out encompassed uniaxial compression tests, diagonal compression tests and shear compression tests, in order to get a comprehensive characterization of basic mechanical properties and of seismic performance of the masonry walls, with and without retrofitting [11].
Within PERPTETUATE project, tests on panels were focused on following main aims: a) to increase the database of reference values of mechanical properties of masonry to be adopted in models; b) to evaluate the effectiveness of some strengthening techniques (such as FRP sheets); c) to provide a correlation between structural and non-structural damage in masonry walls in presence of artistic assets (like as frescos). Tests were performed on brick and stone masonry(both rubble and coursed squared) with two or three leaves (with or without through stones). As regard aims a) and b), both in situ and in laboratory campaigns have been performed addressed to provide a direct characterization of masonry compressive and shear strength: in particular, compression, shear-compression (with single and double fixed condition) and diagonal compression tests have been performed. Moreover, the influence of ageing and deterioration of masonry on load bearing capacity has been analysed [12]. As regard aim c), tests aim at understanding the relationship between the mechanical behaviour of masonry and covering layers under seismic loads: to this aim masonry panels have been covered with different types of plasters aimed to reproduce as far as possible artistic surfaces. Moreover, in some experiments, pre-existing damage patterns on the covering are reproduced, in order to take into account typical decay conditions of heritage buildings. ND tests, like as thermography and radar measurements, have been used to detect the delaminated area of the plaster progressing the non linear response.

4.2. Tests on horizontal diaphragms

The tests on horizontal diaphragms carried out within the NIKER project were mainly aimed at characterizing the in-plane stiffness of horizontal elements, i.e. wooden floors, the formation of a four-hinge collapse mechanisms in brick masonry vaults, and the cyclic behaviour of roof wooden-frames. The in-plane monotonic and cyclic tests on wooden floors were carried out on both reconstructed wooden floor specimens and on-site bare wood or trodden earth floor specimens, before and after intervention. Various strengthening techniques were applied, belonging to three main categories: additional wooden planking, application of diagonal strips, and application of diagonal nets. The brick masonry arches were tested under monotonic and fatigue loading, with intrados and extrados SRP strengthening. Cyclic tests were carried out on brick masonry vaults before and after strengthening by various type of composite materials, such as SRG/P, BTRM, CFRP. The experimental program on roof and floor elements included a series of tests on wooden trusses rescued from existing building, also in relation with the deterioration of the connections, and the physical and mechanical characterization of wooden materials in timber elements. In this case, besides gathering information on the behaviour under cyclic loads of the original and strengthened elements, an effort was also made to develop reliable testing procedures [13].

4.3. Tests on connections

To fill the above mentioned lack of information that is felt in the field of testing and strengthening of structural connections, within the NIKER project three types of experimental set-ups have been adopted. Single structural elements were tested by transmitting the reaction of the remaining part of the connection via a strengthening element; whole connections were tested in either unreinforced or strengthened conditions; and, lastly, entire structures, where strengthening is placed at connections only so as to analyse its effect, were also tested. The types of tested connections cover: connection between two vertical brick masonry walls, in original conditions or strengthened by steel anchors or steel anchors in series with a dissipative anchoring device; GFRP/metallic tie-rods for improving the wall-wall and wall-floor/roof connections in different earthen materials; dovetail halved joints of roof frames in the original conditions and strengthened with damping and/or reinforcing elements; traditional horizontal timber ties at the connection between walls, and between the leaves of multi-leaf stone masonry walls, in timber-laced buildings; traditional rubble stone masonry wall-to-floor timber connections, in unstrengthened conditions and after strengthening. Experimental results give constitutive laws of original and strengthened connections, providing not only information on the load capacity of the connections, but also on energy dissipation, failure modes, performance parameters useful for the development of design and verification procedures [14].

4.4. Shaking table tests on sub-assemblages and full scale samples

The NIKER shaking table test program was divided into two parts: (a) tests on substructures and (b) tests on building models at reduced scale. The assessment of the seismic response of structures through experiments on subassemblies offered the advantage to test specimens at real scale. The experimental work performed on substructures covered the case of shaking table testing of walls under out-of-plane excitations. Two types of masonry were considered: three-leaf stone masonry and adobe, both tested as-built and after strengthening. The former was strengthened by means of transverse steel ties, grouting, and a combination of the two. The latter was reinforced with polyethylene nets mortar joints. Shaking table testing of sub-assemblages also included a brick cross vault, supported by two three-leaf stone masonry walls, where the as-built behaviour was studied, and also the efficiency of various intervention techniques, such as grouting, external vertical prestressing, timber struts/steel ties. Two parallel three-leaf stone masonry walls connected by a timber floor were also tested. This test provided information on the effect of in-plan irregularities on the behaviour of masonry structures; it also examines the efficiency of intervention techniques: grouting of walls and enhancement of the diaphragm action of the floor. The tests on model buildings included 4 specimens made of three-leaf stone masonry with timber floors (regular and irregular, with timber laces or not), in as-built condition, after grout injections of the walls, and with enhancement of the diaphragm action. Further tests were carried out on adobe model buildings with different types of horizontal diaphragms and connections, in the as-built conditions in order to characterize the seismic response under different construction conditions that can be found in real cases [15].

Within PERPETUATE project, shaking table experimental campaigns were addressed to investigate the seismic response of various types of architectural assets (either on full or reduced scale), as: an obelisk, an arch-pier system, a cross vault (tested on the ENEA UTTMAT-QUAL laboratory in Casaccia, Rome) and a multi-drums columns systems (tested on the Soil Mechanics Laboratory of National Technical University of Athens). Main goal of the tests was the evaluation of displacement capacity of such systems and the validation of performance-based seismic analysis procedures developed in the PERPETUATE project. To this aim, given a time-history, the models were subjected to increasing value of PGA up to collapse, thus performing an experimental Incremental Dynamic Analysis (IDA). As regard the obelisk, the 1:6 reduced scale mock-up (composed by three blocks) tested reproduced the Egyptian Obelisk located in piazza S. Giovanni in Laterano (Rome, Italy): it aims to analyse the dynamic response of simple multi-blocks structures, including the original hinge connections system adopted in the real structure that not allow sliding [16]. In case of arch-pier system, both free-standing and reinforced arches were considered: the experimental campaign mainly aims to analyse the influence of tie-rods stiffness on the seismic response to identify the most suitable strengthening strategies to be adopted. The tests showed that reinforced arches collapse with PGA up to 6 times greater than free-standing ones; more flexible tie-rods increases the displacement capacity of the structure and thus the collapse multiplier [17]. In case of the full-scale cross vault sample (that reproduces the geometry of a real cross vault of the Mosque of Dey in Algiers), it aims to analyse the seismic behaviour of vaults by assessing their damage modes and by experimentally evaluating their shear drift. Finally, multi-drums columns systems (representative of ancient temples) have been analysed focusing the attention on the effects of dynamic actions on both sliding and rocking mechanisms among blocks.

5. CASE STUDIES

5.1. NIKER project

One of the main aims of project NIKER is found in the development knowledge-based assessment procedures and their application to real case studies. The proposed seismic assessment procedures involve a variety of activities, such as inspection, monitoring, structural analysis, intervention and quality verification systems. The application to case studies is intended to validate the entire integrated methodology in real site conditions and involves (1) the calibration of monitoring systems and devices; (2) the application of the monitoring systems and devices for the identification of the real behaviour of buildings; (3) the application of the knowledge obtained through monitoring to the creation and updating of reliable structural models; (4) the definition, evaluation and implementation of optimal intervention techniques; (5) the implementation of instrumented dissipative devices; and (6) the assessment of the effectiveness of interventions through optimal quality assessment procedures.
In particular, as far as points 1 and 2 are concerned, the application of monitoring systems involves the measurement of different variables, either environmental or structural, across a long period of time. Continuous static monitoring has consisted of the measurement of a wide variety of variables, both environmental (temperature, humidity, wind parameters) or structural (crack openings, displacements, deformations, work stresses...). Dynamic monitoring systems are intended to measure the dynamic effects on buildings caused by environmental vibrations as well as micro-tremors, earthquake and wind. Some of these systems are being used, to some extent, for early warning purposes (point 5), by means of embedded sensors placed in metallic anchors. All the technologies considered present, to some extent, certain innovation degree in the technological aspects, or in the way they are applied to historical buildings, or in the data analysis process. Because of it, some previous calibration and validation effort has been needed.
The selection of case-studies is intended to cover a wide and representative range of conditions regarding geographical location (different countries) local seismicity (low, medium, high), construction material (stone and brick masonry, earth), structural typologies and uses (towers and minarets, churches, large cathedrals, palaces), preservation condition (different levels of damage) and risks involved (i.e., people at risk, valuable artistic contents at risk). Among the buildings considered are a set of churches in L'Aquila, Italy, a large fortress (Spanish Fortress in L'Aquila), a large Roman construction (Arena in Verona), masonry towers (Civic Tower in L'Aquila) and minarets (a set of Ottoman minarets in Bosnia and Herzegovina), large Gothic cathedrals and monasteries (Mallorca Cathedral, Jerónimos Monastery in Lisbon), masonry buildings (previous Casa de Bragança, now Foundation Headquarter in Lisbon, Mekaad Radwan in Cairo, Ras Cherratine Medersa in Fez, Morocco, the Int. Conservation Centre in Acre, Israel), a former Bizantine church (Hagia Sophia Museum in Trabzon, Turkey), and a large earthen construction (Ambel Preceptory in Ambel, Spain).
All these cases have been carefully analysed and positively evaluated regarding their potential contribution to the validation of the monitoring systems and model updating strategies resulting from the project. Some of them are also considered for the implementation and validation of intervention techniques along with the application of the quality assessment procedures [6].

5.2. PERPETUATE project

Several case studies, aimed to validate the methodology proposed in PERPETUATE project, have been selected in different countries (Italy, Greece, Algeria, Slovenia), like as: 1) the Casbah, the Citadel and Great Mosque in Algiers; 2) some monuments in the historical centre of Rhodes (Greece); 3) Kolizej Palace in Ljubljana (Slovenia); 4) Santa Maria Paganica Church and Ardinghelli Palace in L'Aquila (Italy); 5) St. Pardo Cathedral in Larino (Italy). Each case study provides an exclusive occasion to face the problem of seismic protection of cultural heritage at different scales (single asset or group of buildings in town) and conditions (seismic prevention or reconstruction after an earthquake). Moreover in most of cases, relevant artistic assets are present, allowing us to test results provided by the project also for these "non structural" elements.

In particular, the Casbah of Algiers and the historical centre of Rhodes (both in the UNESCO list of the World Cultural Heritage) are made up of a complex aggregation of historical buildings, which represent a cultural heritage asset as a whole but also contain a wide number of single important monuments. The Casbah of Algiers constitutes a relevant occasion to test the proposed procedure at territorial scale: available models have been updated to take into account the peculiarities of these buildings [7, 18]. In case of Rhodes, the procedure will be applied in a well documented sample of typical and important monumental buildings and residential structures, representative of different periods and morphologies [19]. In both cases, in-situ micro-tremors survey and array measurements have been performed, oriented to both the structural identification and the soil characterization.

The Kolizej Palace in Ljubljana has been a very exclusive occasion to apply several diagnostic techniques (either destructive or not) because Authorities planned its complete demolition [12].

Santa Maria Paganica Church and Ardinghelli Palace in L'Aquila have been strongly damaged by the Abruzzo earthquake on April 6, 2009. Starting from the damage survey, fundamental step to understand the actual seismic behaviour, proper modelling strategies have been adopted for the seismic assessment, in order to decide about the restoration works (due to the high level of damage, many options have been considered: conservation as a ruin, reconstruction with the same or new materials and technologies).

Finally, St. Pardo Cathedral in Larino was slightly damaged by the earthquake in Molise Region, 2002; it is worth noticing that damage was concentrated in those parts that were previously retrofitted.In this case the application of PERPETUATE procedure aims to optimize the knowledge planning [20] and design the technical solutions more appropriate for the seismic improvement of the monument.

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