Protection of the cultural heritage at the ELSA Laboratory

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ABSTRACT: This paper presents a synthesis of the results obtained at the ELSA laboratory from tests on models of historical constructions under earthquake loading. Laboratory tests on large-scale replicas of monumental structures or parts of them were carried out and the results and revisited. Assessment of the efficiency of strengthening solutions and relevance for the calibration and/or development of non-linear numerical models is highlighted. A short summary of the ongoing ELSA activities in the field is given.

1 INTRODUCTION

The European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre at Ispra (VA) is engaged in research in the field of Cultural Heritage through its own institutional programme (financed by the Framework Research Programme of the European Commission). The activities have been initiated through competitive actions performed in close collaboration with international networks (Shared Costs Actions) or Regional Authorities (Technical support to Regions of Southern Europe).

The main objectives in this field are to characterize the behaviour of historical structures under earthquake loading and to contribute to the definition and assessment of retrofitting/repair methodologies.

To reach the objective, an effort has been done to extend the recent advances in earthquake engineering to the structures of the Cultural Heritage. This involves the collaborative use of modern technique methods (Pseudo Dynamic loading) and accurate simulation tools (Finite Element method).

The main results of three projects conducted during these last years were presented in (Pegon et al. 2000) and will be reviewed in this paper. They concern the Geraci Palace in Palermo ("Geraci" project), the S. Vicente de Fora cloister in Lisbon (COSISMO project) and the investigations regarding the use of Shape Memory Alloys as dissipation devices (ISTECH project). Furthermore, a short summary of the ongoing activities at ELSA in the field of masonry and monumental structures is given.

2 THE GERACI PROJECT

The "Geraci Palace" project (Anthoine and Pegon 1998) has been carried out at ELSA from 1995 to 1996, within the framework of a collaboration between the Universities of Catania, Messina and Palermo and the Joint Research Centre of the European Commission (JRC). It was committed by the Authorities of the Sicily Region and was the very first large project carried out in the ELSA Reaction Wall in the field of Cultural Heritage. The main objectives of the project were to set-up a methodology of intervention for the structural strengthening of monumental

structures and to assess the capabilities of the available numerical tools to both predict the earthquake response of this class of structures and design efficient strengthening measures.
Although the particular structure imposed for the study, the “Palazzo Geraci” in Palermo, was neither seismically vulnerable nor susceptible to be repaired, the project provided valuable data for the validation and calibration of numerical models for this kind of limestone masonry building common in southern Italy.

The Geraci Palace is a seventeenth century limestone masonry building of Palermo. It has been profoundly modified at the end of the XVIIIth according to a design by Marvuglia, a famous Italian architect. During the second half of the XIXth, the segmenting of the building into multiple proprieties gave rise to additional structural modifications. The present state of the building (partially destroyed) is due to the second world war air raids. Initially, the central part of this palace was thought to be reproduced as it stood and tested in the Reaction Wall facility of the ELSA laboratory. However, from a preliminary study performed on a three-dimensional finite element model based on photogrammetric measurements, it turned out that such a structure would have been unsuited to the pseudodynamic method since its mass was completely distributed (the floors were lacking). Therefore, it has been decided instead to reproduce in half scale, a part of the palace as it stood before the war: such a choice had the merit of being representative of other buildings in Palermo and well-suited to the pseudodynamic method, since the mass of the floors could be taken into account. Further definition of the experimental model (see Figure 1) was based on intensive linear and non-linear analyses (Anthoine et al. 1999).

Three series of tests have been performed. First, the model has been equipped with base isolation devices (through a sub-structuring technique) and submitted to base accelerations up to 200% of the reference input (test I-200). As expected, the model behaved almost as a rigid body (see (Molina et al. 1998) for a complete report on these tests). Then the isolation devices has been removed and the model has been submitted to three base accelerations of increasing intensity, i.e. 20%, 100% and 200% of the reference accelerogram (tests N-020, N-100 and N-200) until relevant damage could be observed. Finally, the model has been repaired and subjected to 100% and 200% of the reference accelerogram (tests R-100 and R-200) in order to assess the effectiveness of the repair technique. Between each test or intervention, a small amplitude stiffness test has been carried out in order to determine the new stiffness matrix of the model and the corresponding eigenfrequencies (Table 1): this information was required for the integration method and allowed to quantify the degradation/restoration of the model. The damage pattern observed after test N-200 is shown in Figure 2.

The chosen repairing technique consisted in the confinement of the base columns by means of steel strips so as to avoid the expulsion of the limestone blocks. The number of strips has been calculated according to the formula for the shear reinforcement of concrete elements (Eurocode 8. This intervention was very simple (the steel strips were those commonly used for packaging), fully reversible and yielded no disturbance to the integrity of the monument (slight increase of the eigenfrequencies in Table 1). The aesthetic aspect could have been improved by painting the steel strips (see Figure 3).

The repaired model has been subjected again to 100% and 200% of the reference accelerogramme (tests R-100 and R-200). During the first test, the behaviour of the model was fully satisfactory, when compared to the behaviour observed during the test N-100: the structure being less stiff, the displacements were indeed expected to be larger and much more damped (friction in the cracks), but the forces remained of the same order (increase of the ductility). No further damage could be observed despite a noticeable decrease of the eigenfrequencies (Table 1). During the second test, the behaviour of the first story was still satisfactory but the ultimate resistance of the third level was reached. Typical diagonal cracks developed mainly in the two central walls. The comparison of the behaviour of the stories during tests N-200 and R-200 is presented in Figure 4: the first story being slightly stronger, the forces transmitted were able to cause the failure of the third level already initiated during the test N-200.

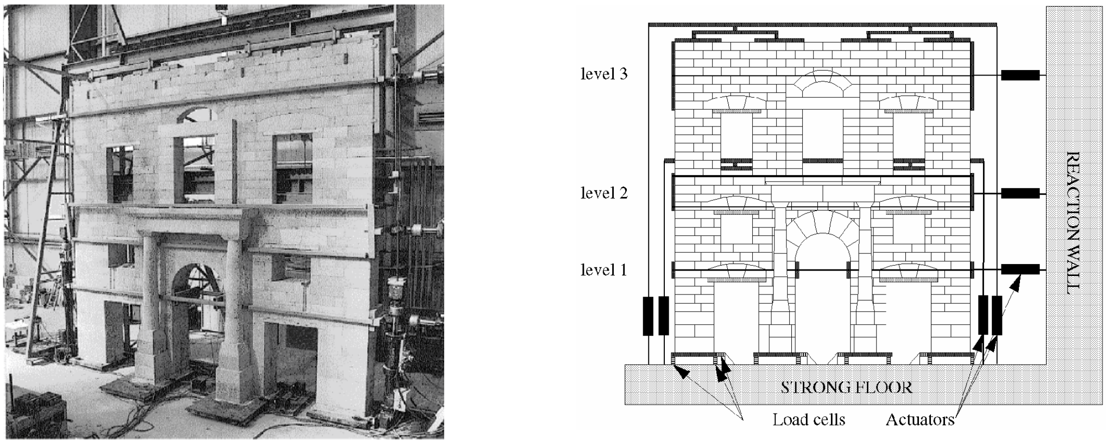

Figure 1: Test Model and loading system

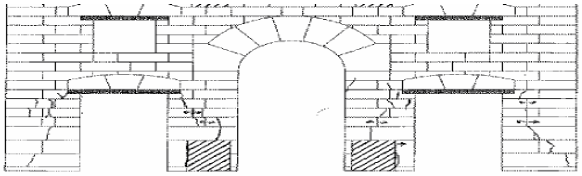

Figure 2: Cracking pattern observed after test N-200

Figure 3: The repaired model

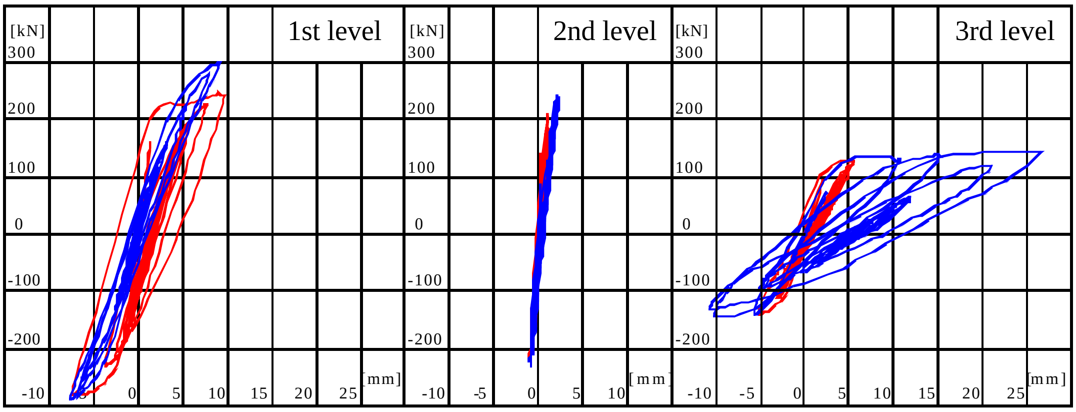

Figure 4: Interstorey shear-displacement curves during tests N-200 (grey) and R-200 (black)

Table 1. Evolution of the eigenfrequencies of the model during the test program

Frequency (Hz) after …	Curing	I-200	N-020	N-100	N-200	Repair	R-100	R-200
First mode	8.28	8.23	7.99	7.31	5.64	6.39	5.56	4.34
Second mode	19.1	18.9	19.1	16.6	14.0	15.5	13.8	10.6
Third mode	79.0	74.9	80.2	74.1	71.9	74.1	68.4	65.5

3 THE COSISMO PROJECT

The COSISMO project has been carried out conjointly by the National Laboratory of Civil Engineering (LNEC) in Lisbon and ELSA, from 1996 to 1998. It was committed by the Portuguese General-Directorate for National Buildings and Monuments (DGEMN) and concerned the São Vicente de Fora monastery in Lisbon, which is a typical monument of Lisbon from an architectonic/engineering point of view. Although the monument survived the catastrophic November 1st, 1755 earthquake, it suffered severe damages, some of which are still visible today. Since a quite detailed description of these damages is available, their prediction using the present modelling capabilities calibrated on the basis of the experimental results obtained by ‘in situ’ tests and by laboratory tests was a great challenge.

The COSISMO project included the following main tasks: 1) Dynamic characterisation of the Monastery by in situ testing and numerical modelling; 2) Laboratory testing of a model representative of part of the structure in order to calibrate and/or develop non-linear numerical models to be used for predicting the earthquake response of such structures; 3) Development and calibration of non-linear and equivalent linear models appropriate for high intensity shaking; 4) Assessment of the seismic vulnerability of the Monastery, using the developed and calibrated models and appropriate seismic hazard characteristics; 5) Investigation of the applicability of some retrofitting solutions and techniques for monumental structures.

The test model has been defined so as to both represent typical monumental structures (full-scale partial model) and reproduce construction techniques realistic in terms of materials, scale and stone arrangements. Four numerical analyses, using the same elastic block/non-linear joint approach as for the Geraci palace, have been performed in order to pass progressively from the actual monument to the test model (Pegon and Pinto 1996, Pegon and Pinto 1998). First, the complete facade of the cloister has been considered as a periodic structure. Second, the upper storeys have been replaced by an equivalent distributed loading. Third, the distributed vertical loading has been substituted by a concentrated one. Finally, since the periodic boundary conditions (i.e. equal vertical and horizontal displacements of the two lateral end-sides) would have required a very complex set-up, the model has been increased from one to three columns with a horizontal post-tensioning (Figure 5). This latter solution had the merit of representing not only the central part of the long façade (central column and half-arches) but also its lateral parts (external columns and half-arches). Three vertical servo-actuators, located at the vertical of the columns, provided the vertical forces due to the missing upper part of the monument and compensated the overturning moment due to the horizontal force applied at the top of the model. A uniform distribution of horizontal forces resulting from earthquake excitations was guaranteed by an 'original' loading system made of interconnected water-pad bearings (detail at top-left-side of Figure 5).

The test model (Figure 6) has been built using materials and construction techniques (stone blocks arrangement) similar to the prototype cloister facade. The upper part of the model was made of stone masonry. Three millimetres thick mortar joints were assured during the construction. The characterisation of the model has been performed first (modal and stiffness tests), in order to obtain the initial stiffness, frequencies and mode shapes and to evaluate damping for very low displacement levels. Afterwards, three pseudo-dynamic tests were performed. The system reducing to one-degree of freedom, the value of the translation mass (400 tons) has been chosen so as to obtain a frequency value of 4Hz, in agreement with analytical and experimental studies performed on the original monument (Dyngeland et al. 1998)(Campos-Costa et al. 1997). Since two earthquake scenarios should be considered for Lisbon (far-field and near-field), two different earthquake accelerograms response spectra were used, each one having a rather different energy content. The energy of the near-field accelerogram response spectrum was mainly in the higher frequency range (above 2 Hz), whereas the far-field accelerogram response spectrum was characterised by a low frequency energy content. Based on these spectral differences and on the pre-test numerical simulations, the following tests were performed. A low-level seismic test has been carried out with a near-field accelerogram (174 years return period) and a high level test has been performed with a far-field accelerogram (975 years return period). After this latter test, an additional pseudo-dynamic test has been carried out with the same input signal multiplied by a factor of 1.5.

Then, two cyclic quasi-static tests have been performed in order to calibrate analytical models, to study the effect of the pre-compression force (10t or 5t) on the behaviour of the façade and to obtain a basis of comparison for assessing the effectiveness of the retrofitting technique. The imposed increasing-displacement histories had two constant amplitude cycles for each level and ranged from 8 to 100mm. The corresponding force-displacement diagrams are both very similar to what was observed during the high-level earthquake test. Equivalent strengths were developed for the maximum amplitude (100mm). However, the transition between the two stiffnesses (i.e. between closing and opening of the column-block joints) was smoother when the compression was higher. Therefore, it was concluded that 'a minimum' pre-compression level should be applied in order to maintain stability of the upper part of the façade and to improve deformation capacity of these kind of structures. Furthermore, it was verified that compression forces higher than a minimum limit do not improve significantly the cyclic performance of the structure, at least for the experienced deformation amplitudes.

The model has been retrofitted with four internal continuous bond anchors, two at each level with 2 meters overlapping (Figure 5). The anchors have been placed in horizontal holes drilled from each end side of the model, anchored and pre-tensioned at 20 kN before the grouting of the holes.

Three cyclic tests were performed on the retrofitted model. The first one has been carried out with a pre-compression force of 5t and for displacement amplitudes ranging from 8 to 30mm. Then the pre-compression force has been reduced to 1.25t and the displacement amplitudes have been increased from 30 to 100mm. Finally, the pre-compression has been completely removed and the model submitted to displacement amplitudes ranging from 8mm to 60mm. Although the diagrams are very similar, the retrofitted model exhibited a noticeably different behaviour: the elongation of the upper part was much larger and, furthermore, irreversible while the initial length of the original model was almost completely recovered at the end of the test.

'Only' local damages were observed during the tests, namely slight dislocation of column and arch stone-blocks (15 mm maximum value), crushing and 'delamination' of stone blocks at the most stressed contact zones, large cracks in the masonry between contiguous arch-bases and passing through the upper columns and failure (spalling) of a few limestone cover plates (see Figure 7 - left). Furthermore qualitative agreement could be found with the preliminary analytical results (see Figure 7 - right). The modelling had been further extended to account for the complete 3D geometry of the model (Ambrosetti and Pegon 1998, Pegon et al. 1999).

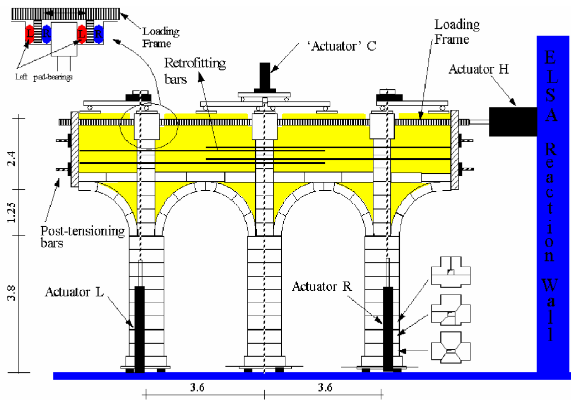

Figure 5: S. Vicente de Fora: model - Test set-up (schematic)

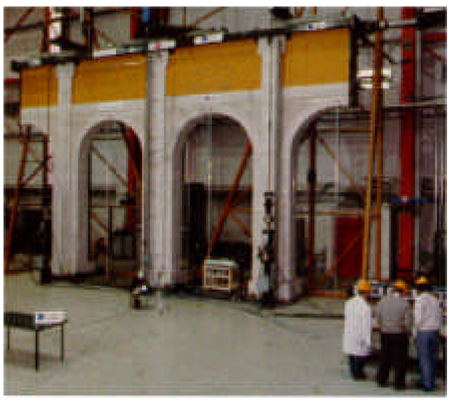

Figure 6: Façade full-scale model in the ELSA reaction wall laboratory

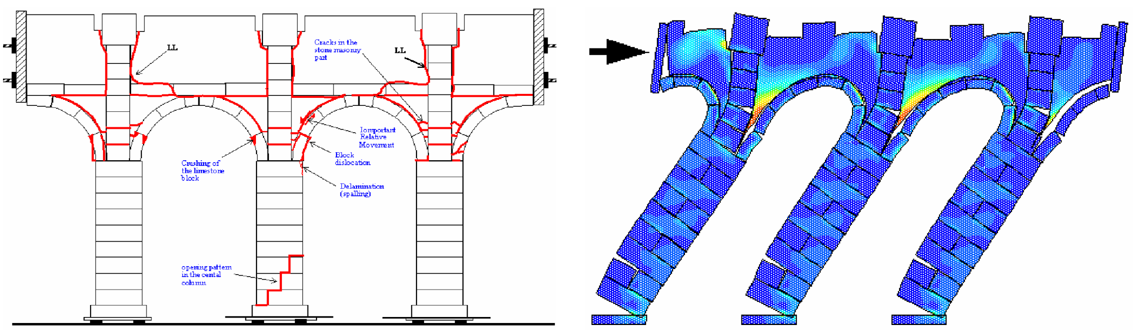

Figure 7: Damage and Deformation: a) Damage from tests, b) Deformation pattern (analytical results)

4 THE ISTECH PROJECT

The ISTECH project *(Innovative Stability Techniques for the European Cultural Heritage)* was a shared-cost action supported by the European Commission DGXII for the Environment and Climate programme. Carried out from 1997 to 1999 by a consortium of 6 partners, its aim was to develop and assess, both numerically and experimentally, a new seismic protection method for ancient structures. Indeed, traditional strengthening techniques are not always effective and are often considered too invasive as they modify the integrity of the original historical structure.

Moreover, innovative seismic protection systems, such as the base isolation technique, widely adopted in new earthquake resistant constructions, are not easily practicable for existing structures. The protection method developed and assessed during the project, is a cross-bracing system based on shape memory alloys (SMAs) devices and susceptible to protect walls subjected to in-plane seismic loading through energy dissipation and strengthening by compression.

SMAs exhibit a super-elastic behaviour through a phase change from Austenite to Martensite and vice-versa. Their stress-strain cycles produce dissipation without any damage for moderate strain (<7.5%) and, if performed in tension, allow the use of thin wires for the realisation of the devices. A preliminary experimental campaign (Tirelli et al. 1999) has been therefore conducted on wires of different sections, to define their stress-strain behaviour and energy dissipating capacity under cyclic loads and to choose the best performing alloy to be use in the cross-bracing system. Both static (low strain rate) and dynamic tests have been performed.

Subsequently, in order to assess the effectiveness of the cross-bracing system for the seismic protection of ancient structures, the behaviour of brick masonry walls under seismic loads was investigated at the ELSA laboratory (Bono et al. 1998, Renda et al. 1997). Three identical specimens representing a masonry house façade with two doors and thus three shear walls (Figure 8) have been built with bricks and mortar arranged in a three-brick-width thickness pattern on a reinforced concrete basement. A reinforced concrete slab has been added at the top of each specimen in order to distribute the forces applied by the servo-actuators, one horizontal at one extremity and two vertical (Figure 9). A traditional approach in the retrofitting of existing structures consists in the connection and prestressing of the walls by means of tendons. As the preliminary FEM analyses showed crack propagation in the upper part, it was decided to place an horizontal tendon just above the openings of the wall. The forces applied by means of the 2 vertical actuators (see Figure 9) represented the weight of the remaining superior levels and the missing floors. Each specimen was thus subjected to its self-weight and to an additional vertical load of 630 KN. This resulted in a mean value of the compression stress of 0.6 MPa at the base of the wall, considered as being representative of ancient masonry buildings. The vertical loading system allowed, at the same time, to avoid the rotations of the upper level, in the hypothesis of the continuity of the masonry façade.

The numerical analyses were first performed using the same block/joint approach (Pegon et al. 1999) as for the two other projects. However, due to the small size of the bricks with respect to the wall, it has been found more rational (and less CPU time consuming!) to consider a continuous modelling using a concrete-like model (in this case the Ottosen fixed multi-crack model with an explicit dependence on the fracture energy (Dahlblom and Ottosen 1990)). A special strut model has been introduced for simulating the SMAs (Bono et al. 1998).

The first specimen has been subjected to cyclic quasi-static lateral displacements of increasing amplitude up to a maximum value of 12mm. At this stage, the specimen exhibited important damages consisting mainly in large diagonal cracks in the three lower panels starting from the central one (see Figure 10). This preliminary cyclic test allowed the calibration of a non-linear numerical model, based on finite elements, for the investigation of the dynamic behaviour of the unprotected wall and the design of suitable cross-bracing systems. In particular, the value of the pre-tension in the SMAs as well as the number of SMAs wires had to be chosen so as to optimise both the strengthening due to compression and the damping due to dissipation. When compared with the experimental results, FEM analyses showed a slight minor hysteresis during cycling.

The second (unprotected) specimen has been tested pseudo-dynamically under a sequence of seismic excitations having the same shape (a reference artificial accelerogram with a peak acceleration of 1.18 ms^{-2}) but increasing amplitudes chosen on the basis of numerical simulations. The façade being a one-degree of freedom system, the value of the translation mass (78 tons), comprehensive of the real masses, the experimental hardware and the overloads, has been chosen. This leads to an initial frequency value of about 7.5Hz. For the first test, the amplitude was 70% of the reference accelerogram and the response of the specimen remained linear without any visible damage. The second and third tests have been performed with the same amplitude namely 200% of the reference signal. During the first run, some cracks appeared mainly in the central wall. During the second run, the damages increased (more and wider cracks) and occurred also in the two lateral walls. Finally, a fourth test performed for 300% of the reference input, has been interrupted at midway since the overall stability of the specimen was jeopardised by large cracks present in all walls.

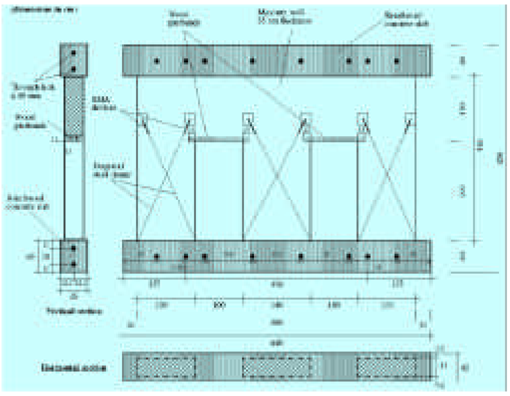

Figure 8: Design of the masonry façade specimen

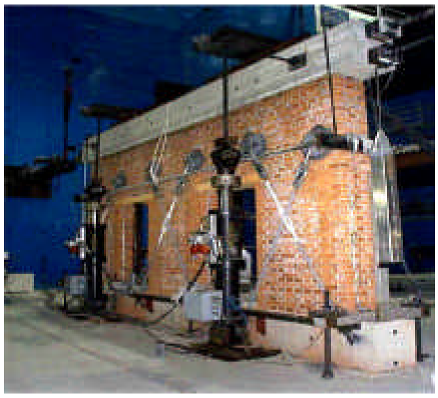

Figure 9: Masonry façade equipped with the cross-bracing systems and ready for testing

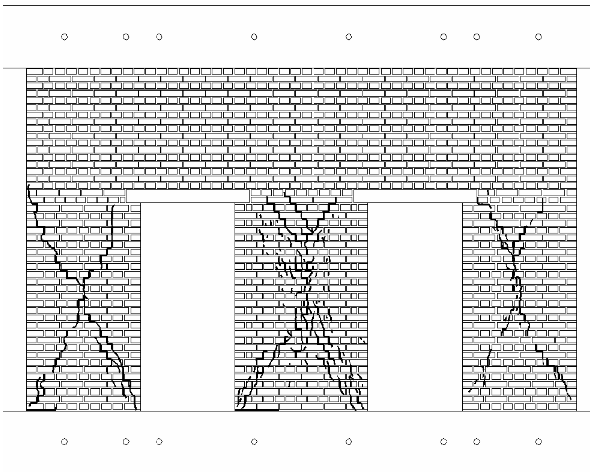

Figure 10: Cyclic test: failure damage pattern

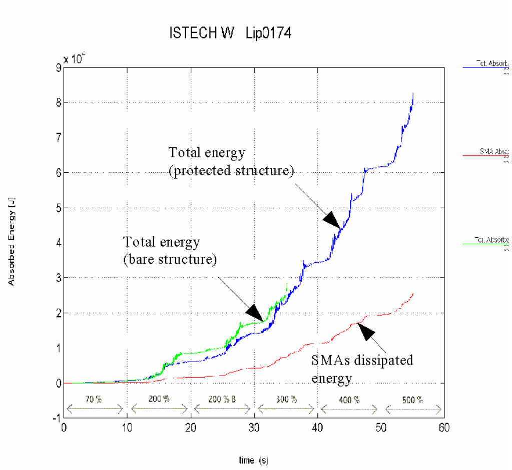

Figure 11: Dissipated energy during the PSD tests

The third specimen has been equipped with the three cross-bracing systems, one for each wall (see Figure 8 and Figure 9), and the tests performed on the second (unprotected) specimen have been repeated with the same sequence. Until 300% of the reference signal, some dissipation of energy has been measured but no crack was visible. It has been decided to run a fifth test for 400% of the reference signal during which some cracks appeared but only in the central wall. Finally, a sixth test performed for 500% of the reference input, induced large cracks both on the central and lateral walls. Again it has been interrupted at midway for safety reasons although the force-displacement curves were still exhibiting a good shape and the SMAs devices were working correctly.

The respective performance of the unprotected and protected facades can be compared in terms of dissipated energy. As can be seen on Figure 11, the energy dissipated by the SMAs devices amounted to about 30% of the total energy.

5 ONGOING ACTIVITIES

ELSA is presently devoting attention to assessment and retrofitting of masonry structures and is also confronted with a challenging and ambitious project in the field of protection of cultural heritage, which should assist authorities to define their policies, in particular in the prioritization of the interventions. It is requested to provide support to decision-makers with simplified, yet reliable tools allowing for an automatic/semi-automatic assessment of the vulnerability and risks on the basis of existing engineering information and/or an automatic 3D reconstruction of the existing monuments using advanced laser based devices.

5.1 *Seismic Assessment Repair and Retrofit of Masonry Structures*

Redesign after earthquake damages and retrofitting against expected earthquakes are essential parts of the entire process for seismic protection. The seismic Eurocode (EC8) includes a section called “Repair and Strengthening” (Part 1.4). This section contains a quite general framework dealing with assessment, decision-making and redesign as well as concise descriptions of intervention techniques for different materials including masonry structures (Annex K). Particular considerations for historical buildings and monuments are also given (Annex F).

In load-bearing masonry constructions, masonry walls usually carry both gravity and lateral loads. Under seismic lateral loads, masonry buildings may collapse due to the in-plane and/or out-of-plane failure of these walls. The in-plane failure may occur according to flexural, sliding or shear modes. The latter mode is by far the more likely and usually takes place in the form of one or two diagonal cracks. Many repair/strengthening techniques are presently available for masonry walls exposed to such a failure mode. Some of these have been applied for years on existing structures but have not always been tested in a systematic way, others have been proposed recently and have not been used in practice nor even tested yet. In particular, basic data about the respective performances of traditional/innovative techniques as well as advanced numerical tools able to reproduce the cyclic in-plane behaviour of plain/reinforced masonry are still lacking.

This institutional project is intended to fill these gaps and thus to allow the development of design guidelines for the repair and strengthening of masonry buildings, monuments and other constructions typical of the European Cultural Heritage. To this end, an experimental campaign has been designed in order to assess the efficiency of traditional and innovative repair/strengthening techniques and also to allow the calibration/development of advanced numerical models for masonry with particular emphasis on the in-plane cyclic behaviour. A view of the experimental set-up and numerical simulations are given in Figure 12. Details can be found elsewhere (Molina et al. 2001, Le Pape et al. 2001).

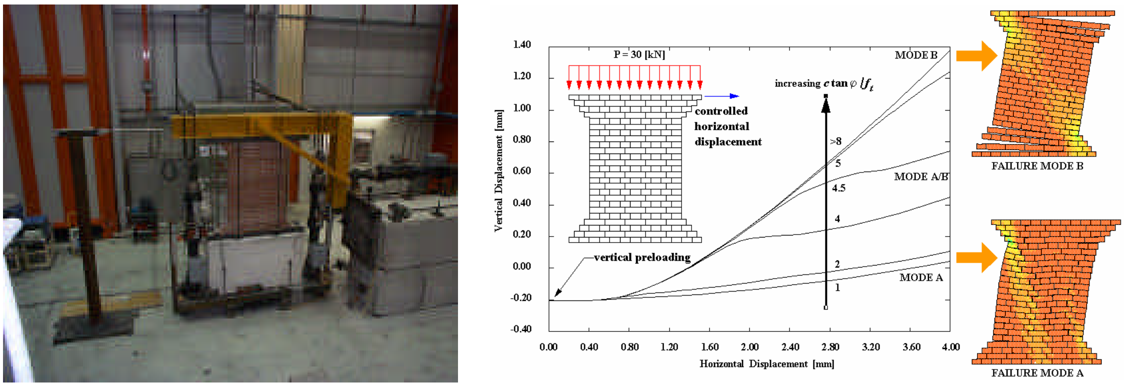

Figure 12: Research on masonry: a) Experimental set-up, b) Numerical simulation

5.2 *Automatic 3D Reconstruction Using Advanced Laser-based Devices*

The modelling capabilities of ELSA provide realistic 2D or 3D simulation of the behaviour of historical monuments There is however an important bottleneck preventing them to be used intensively: the mesh generation. Indeed the generation of the mesh representing the structure of a monument is time consuming since it is based on manual input either from the construction drawings or from the existing buildings. There is thus the need for automating this phase of the seismic analysis, specifically there is a need for development of a semi-automated system able to translate a 3D Reconstructed model from an old building/monument "as built" to a structural representation that can be used for seismic simulation and assessment (Pegon et al. 2001b). Such a tool would be most beneficial in: a) the analysis and identification of heritage buildings where need of restoration is urgent; b) obtaining the electronic description of the building, i.e., CAD model; c) using the 3D model for visualisation purposes.

The competences on 3D reconstruction already exist as well as the earthquake vulnerability analysis tools developed at ELSA. The objective is now to combine and exploit these available competences and to progress towards an integrated automatic, or at least, semi-automatic system, which will open the doors for much more ambitious projects in the field of seismic protection of the European Built Cultural Heritage.

Indeed, authorities in charge of preservation of buildings with cultural value should manage the available resources on the grounds of prioritisation programmes, which take into account risk and exposure costs. The former are directly related with the proposed integrated system, which will allow for rapid screening of the vulnerabilities on the basis of the existing information and/or the 3D reconstruction, which information is transformed to readable input for structural analysis programs. Then, the convolution of these vulnerabilities with hazard will find the risk levels.

The realization of the overall work is split into two phases (respectively the solid and the dashed arrows in Figure 13): a) 1st phase (solid arrows) - Development of semi-automatic algorithms for the construction of 3D meshes, CAD maps and Drawings from 3D Reconstructed model; b) 2nd phase (dashed arrows) - Construction of 3D meshes, CAD maps and 3D Reconstructed model from Drawings.

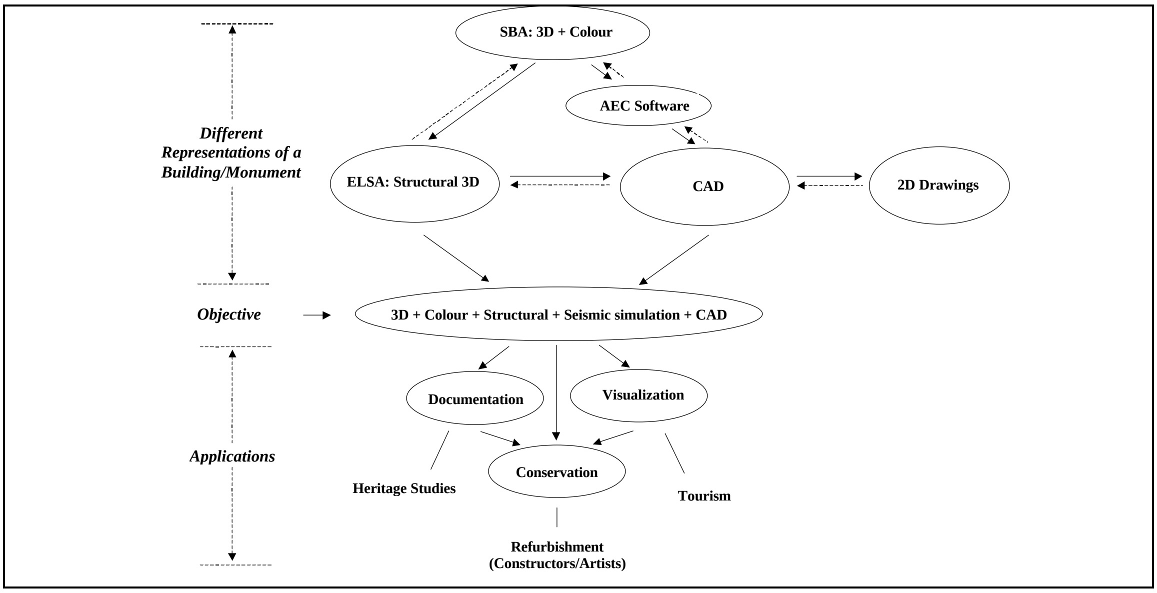

Figure 13: Integration of 3D Reconstruction and Seismic Analysis for Virtual Heritage (Schematic representation of the envisaged levels and tools) - (AEC: Architecture, Engineering and Construction)

6 CONCLUSIONS AND PERSPECTIVES

The projects outlined in this paper demonstrate that, if carefully designed, laboratory tests on large-scale replicas of monumental structures allow to assess the efficiency of strengthening solutions and enable the calibration and/or development of non-linear numerical models for predicting the earthquake response of such structures.

Various types of retrofitting techniques have been evaluated, very simple (confinement of the columns with steel strips), more complex to implement (pre-compression ties and further continuous-bond anchor) or highly technological (use of SMA devices).

Numerical modelling was fully used for the design of the structures to be tested, the loading devices and the loading intensity. A block/joint approach or a more conventional continuous approach had been introduced for this purpose. Although good qualitative and reasonable quantitative results can be obtained, the predictive character of the models is not yet completely assessed. This can be mainly attributed to the lack of a satisfactory modelling of the masonry subjected to cyclic loading. To fill this gap, as part of its institutional activities, ELSA is currently performing analytical and experimental basic studies on this material, together with the evaluation of the various means to reinforce/retrofit it.

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