Improving the seismic resistance of cultural heritage buildings

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ABSTRACT: The paper addresses a possible methodology to improve the seismic resistance of cultural heritage buildings (CHB). The ICOMOS recommendations are briefly reviewed and recent research issues are addressed, with a focus on: (a) Behavior of masonry components under cyclic loading (tension, compression and shear); (b) Behavior of stone masonry shear walls under cyclic and dynamic loading; (c) Behavior of dry masonry blocks and structures under dynamic loading; (d) Possibilities of numerical analysis at the laboratory and engineering levels; (e) Monastery of Jerónimos as a case study: An EC funded research project aiming at reducing seismic vulnerability of CHB.

1 INTRODUCTION

Modern societies understand built cultural heritage as a landmark of culture and diversity. Only during the last decades the idea that old and ancient buildings could be restored and reused became appealing for the market. In fact, the present policy is not only to preserve but also to make buildings and the historic part of the cities alive, functioning and appealing to the inhabitants and to the tourists.

Nevertheless due to the effects of aggressive environment (earthquakes, soil settlements, traffic vibrations, air pollution, etc.) and to the fact that many old buildings and historic centers were not subject to continuous maintenance, a large part of this heritage is affected by structural problems that menace the safety of buildings and people.

European countries have developed a valuable experience in conservation and restoration. In recent years, large investments have been concentrated in this field, leading to impressive developments in the areas of inspection, non-destructive testing, monitoring and structural analysis of historical constructions. These developments, and the recent guidelines for future reuse and conservation projects, allow for safer, economical and more adequate remedial measures.

Being earthquakes a major source of destruction of cultural heritage buildings, see Figure 1, this paper focus on recent advances and aspects under investigation at University of Minho.

(a)

(b)

Figure 1. Historical citadel of Arg-e-Bam and the earthquake of December 2003: (a) before and (b) after.

2 ICOMOS RECOMMENDATIONS

Structures of architectural heritage, by their very nature and history (material and assembly), present a number of challenges in conservation, diagnosis, analysis, monitoring and strengthening that limit the application of modern legal codes and building standards. Recommendations are desirable and necessary to both ensure rational methods of analysis and repair methods appropriate to the cultural context.

Therefore, an international committee has prepared recommendations, intended to be useful to all those involved in conservation and restoration problems, Icomos (2001). These recommendations contain Principles, where the basic concepts of conservation are presented, and Guidelines, where the rules and methodology that a designer should follow are discussed. More comprehensive information on techniques and specific knowledge can be found, e.g. in Croci (1998), Giuffrè (1993) and Meli (1998).

2.1 *Principles and Guidelines*

The principles entail: General criteria; Research and diagnosis; and Remedial measures and controls. A multi-disciplinary approach is required and the peculiarity of heritage structures, with their complex history, requires the organization of studies and analysis in steps: condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions. Understanding of the structural behavior and material characteristics is essential for any project related to architectural heritage. Diagnosis is based on historical information and qualitative and quantitative approaches. The qualitative approach is based on direct observation of the structural damage and material decay as well as historical and archaeological research, while the quantitative approach requires material and structural tests, monitoring and structural analysis.

Often the application of the same safety levels used in the design of new buildings requires excessive, if not impossible, measures. In these cases other methods, appropriately justified, may allow different approaches to safety. Therapy should address root causes rather than symptoms. Each intervention should be in proportion to the safety objectives, keeping intervention to the minimum necessary to guarantee safety and durability and with the least damage to heritage values. The choice between "traditional" and "innovative" techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability. At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest "an observational method", i.e. an incremental approach, beginning with a minimum level of intervention, with the possible adoption of subsequent supplementary or corrective measures.

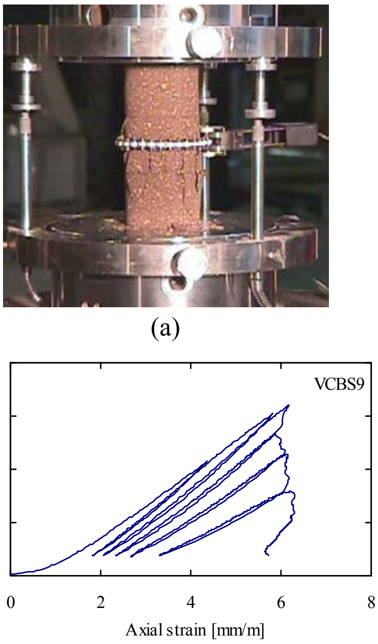
The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term effects, so that undesirable side effects are avoided.

3 EXPERIMENTAL ISSUES

Masonry is a heterogeneous material that consists of units and joints. Units are such as bricks, blocks, ashlars, adobes, irregular stones and others. Mortar can be clay, bitumen, chalk, lime/cement based mortar, glue or other. The huge number of possible combinations generated by the geometry, nature and arrangement of units as well as the characteristics of mortars raises doubts about the accuracy of the term "masonry". Nevertheless, most of the advanced experimental research carried out in the last decades has concentrated in brick / block masonry and its relevance for design. Accurate modeling requires a thorough experimental description of the material, see Lourenço (1998) and Cur (1997).

3.1 *Properties of unit and mortar*

The properties of masonry are strongly dependent upon the properties of its constituents. Compressive strength tests are easy to perform and give a good indication of the general quality of the materials used. Experiments about the uniaxial post-peak behavior and about the biaxial behavior of bricks and blocks are less common in the literature, together with tests on cyclic behavior. Next, some results for clay bricks under uniaxial compression are briefly reviewed (Oliveira 2002). A series of unloading-reloading cycles were performed in clay specimens, particularly in the post-peak region, to acquire data about stiffness degradation and energy dissipation. The experimental set-up, testing conditions and typical stress-strain diagrams are illustrated in Figure 2. The need for circumferential displacement control is stressed, and the results shown are rather difficult to obtain due to very high strength and brittleness of the units used in the testing program. The response indicates an important and monotonic decrease in Young's modulus in the post-peak regime, associated with damage growth in the material.



(a)

(b)

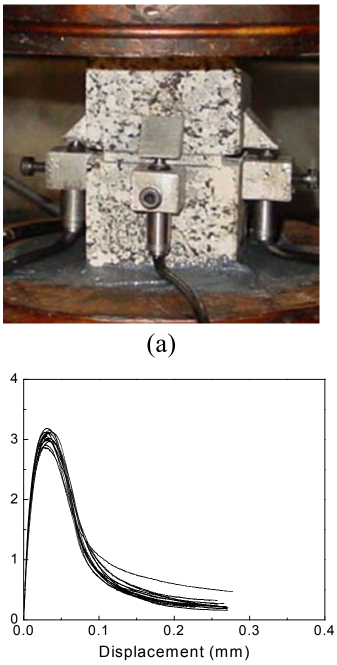
Figure 2. Aspects related to the cyclic behavior of masonry units under uniaxial compression: (a) cylindrical brick specimen under testing conditions, and (b) typical stress-strain diagram.

With respect to the tensile strength of the masonry unit, extensive information on the tensile strength and fracture energy of units can be found in Lourenço et al. (2005) and Vasconcelos et al. (2005), see Figure 3. The difficulties in relating the tensile strength of the masonry unit to its compressive strength are well known, not only due to the different shapes of the units but also to the different materials.

For the mortar, standard test specimens are cast in steel moulds and the water absorption effect of the unit is ignored, being thus non-representative of the mortar inside the composite. Investigations in mortar disks extracted from the masonry joints are being planned at University of Minho.

3.2 *Properties of the interface*

Bond between unit and mortar is often the weakest link in masonry assemblages. The non-linear response of the joints, which is then controlled by the unit-mortar interface, is one of the most relevant features of masonry behavior. Two different phenomena occur in the unit-mortar interface, one associated with tensile failure (mode I) and the other associated with shear failure (mode II). Different test set-ups have been used for the characterization of the tensile behavior of the unit-mortar interface. For the purpose of numerical simulation, direct tension testing should be adopted because it allows for the full representation of the stress-displacement diagram and yield the correct strength value. No tests seem to be reported with respect to the behavior of the interface under cyclic tension.



(a)

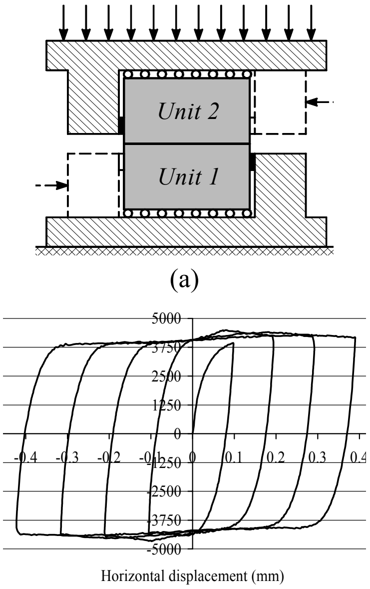
(b)

Figure 3. Aspects related to the behavior of masonry units under tension: (a) notched stone specimen under testing conditions, and (b) typical stress-strain diagrams.

Adequate characterization of masonry shear behavior under cyclic loading is given in Lourenço & Ramos (2004), as shown in Figure 4. The experimental set-up has been designed so that the bending effects associated with shear testing are minimized. The vertical confining pressure is kept constant while the test is carried out under horizontal displacement control. Almost zero dilatancy has been found during each cycle. The tests indicate that the shear inelastic deformation is fully plastic (or irreversible).

3.3 *Properties of the composite material*

The compressive strength of masonry in the direction normal to the bed joints has been traditionally regarded as the sole relevant structural material property. Since long it has been accepted by the masonry community that the difference in elastic properties of the unit and mortar is the precursor of failure, but this seems hardly correct (Pina-Henriques and Lourenço, 2005) and Figure 5. Uniaxial compression tests in the direction parallel to the bed joints have received substantially less attention from the masonry community.



(a)

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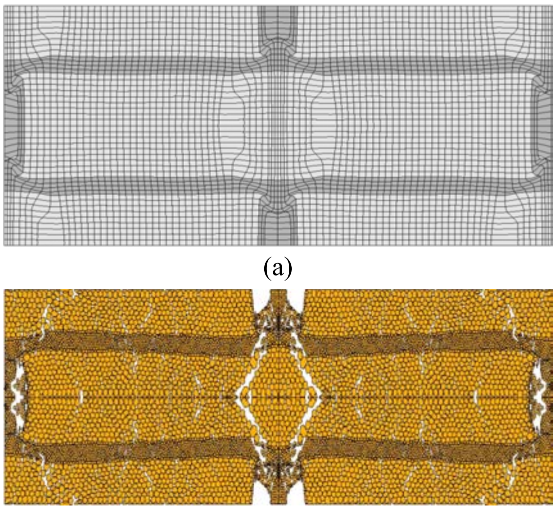
Figure 4. Aspects related to the cyclic behavior of masonry joints under shear: (a) specimen under testing conditions, and (b) typical stress-strain diagram.



(a)

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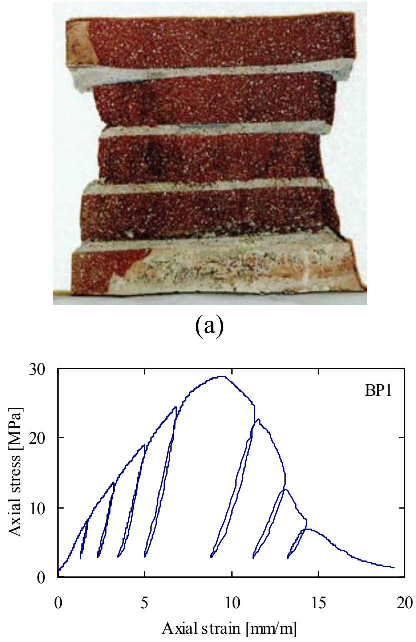
Figure 5. Simulation of a masonry representative volume under compression: (a) continuum model, and (b) particulate model. The differences found in terms of simulated compressive strength are up to 30%.

Next, some results for masonry specimens under uniaxial compression (Oliveira, 2002) are briefly reviewed. A series of unloading-reloading cycles were performed, particularly in the post-peak region, to acquire data about stiffness degradation and energy dissipation. The typical failure and stress-strain diagrams are illustrated in Figure 6. Apart from the initial adjustment between the prism and the machine platens, stress-strain curves exhibited a pre-peak bilinear behavior, which has been reported by other authors. An initial linear branch was followed by another branch up to near the peak, with lower stiffness and greater development. The response clearly indicates an important and monotonic decrease in Young's modulus in the post-peak regime, associated with damage growth in the material.



(a)

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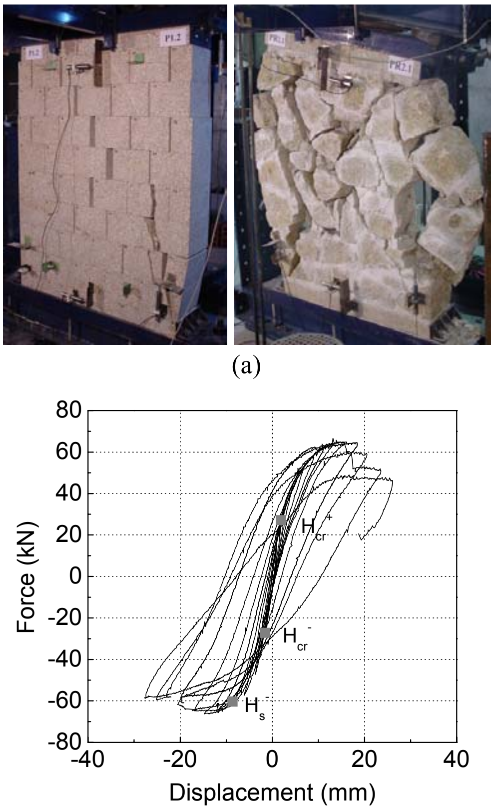
Figure 6. Aspects related to the cyclic behavior of masonry specimens under uniaxial compression: (a) typical failure of masonry specimen and (b) typical stress-strain diagram.

3.4 *Stone masonry shear walls*

Although traditional historic masonry walls can be viewed as unsuitable structures to undergo seismic actions, they, in fact, exist and frequently represent the major structural elements of ancient buildings. Brick unreinforced masonry walls have been widely studied both from experimental and numerical point of view, but scarce experimental information is available for stone masonry walls.

Therefore, a comprehensive testing program was started at University of Minho and National Technical University of Athens, aiming at increasing the insight about the behavior of typical ancient masonry walls under cyclic loading and dynamic loading (Vasconcelos 2005). Besides the strength and stiffness characterization, information about nonlinear deformation capacity was obtained in terms of ductility factors and lateral drifts, which represents a step forward for the new concepts of performance based design.

Regular and irregular stones have been adopted, see Figure 7. Although no significant differences were found in terms of strength and lateral stiffness among the distinct types of walls, low mortared strength masonry walls exhibit markedly higher level of energy dissipation when compared with dry stacked masonry.



(a)

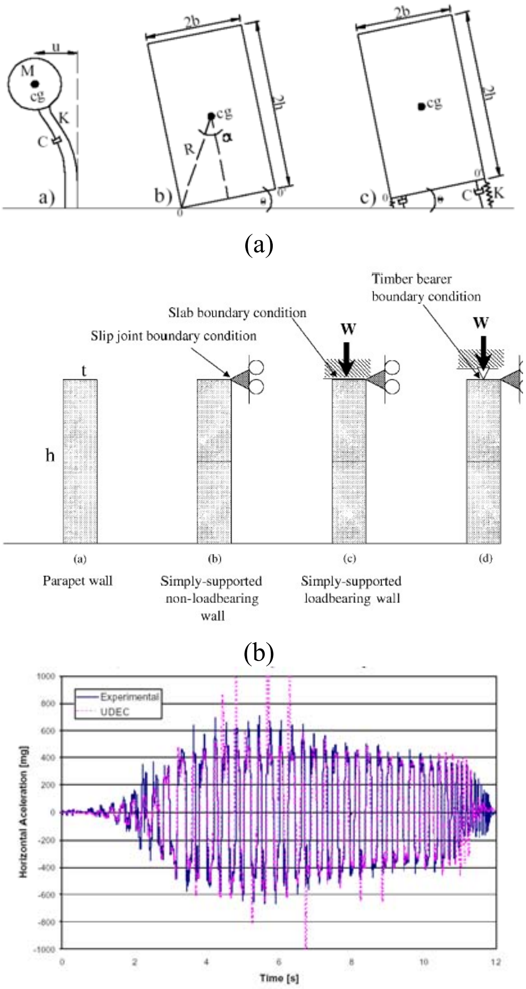
(b)

Figure 7. Behavior of stone masonry walls with different bond: (a) failure modes and (b) selected force-displacement diagram.

3.5 *Dry blocky stone masonry structures*

The behavior of masonry can often be associated with dry blocky structures, which feature zero tensile strength in the joints but horizontal tensile strength and shear strength due to frictional effects. Limit analysis simulations are often used in practice for safety assessment and strengthening design. In order to extend limit analysis formulation to include dynamics and in order to study out of plane seismic behavior of masonry walls, another comprehensive testing program was set-up at University of Minho and National Laboratory of Civil Engineering (LNEC, Portugal).

Figure 8 illustrates the details of the testing program, including simplified analysis models, structures under analysis and results. Currently, tests of single blocks, two blocks, a dolmen structure and an arch are being carried out.



(a)

(b)

(c)

Figure 8. Dynamic behavior of blocky stone structures: (a) simplified models for analysis, (b) possible out-of-plane conditions for masonry walls, and (c) typical experimental / numerical results for hanning sinusoidal forced vibration.

4 NUMERICAL ISSUES

Masonry is a material exhibiting distinct directional properties due to the mortar joints, which act as planes of weakness. Depending on the level of accuracy and the simplicity desired, it is possible to use the modeling strategies shown in Figure 9. One modeling strategy cannot be preferred over the other because different application fields exist for micro- and macro-models. Micro-modeling studies are necessary to give a better understanding about the local behavior of masonry structures. This type of modeling applies notably to structural details. Macro-models are applicable when the structure is composed of solid walls with sufficiently large dimensions so that the stresses across or along a macro-length will be essentially uniform. Clearly, macro modeling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation.

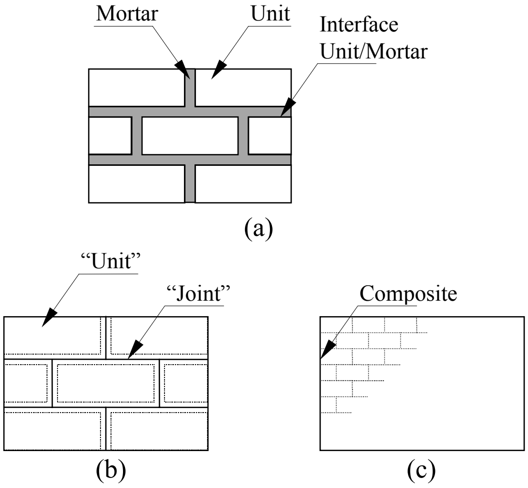


Figure 9. Modeling strategies: (a) masonry specimen, (b) micro-modeling and (c) macro-modeling.

Linear elastic analysis can be assumed a more practical tool, even if the time requirements to construct the finite element model are the same as for non-linear analysis. But, such an analysis fails to give an idea of the structural behavior beyond the beginning of cracking. Due to the low tensile strength of masonry, linear elastic analyses seem to be unable to represent adequately the behavior of historical constructions.

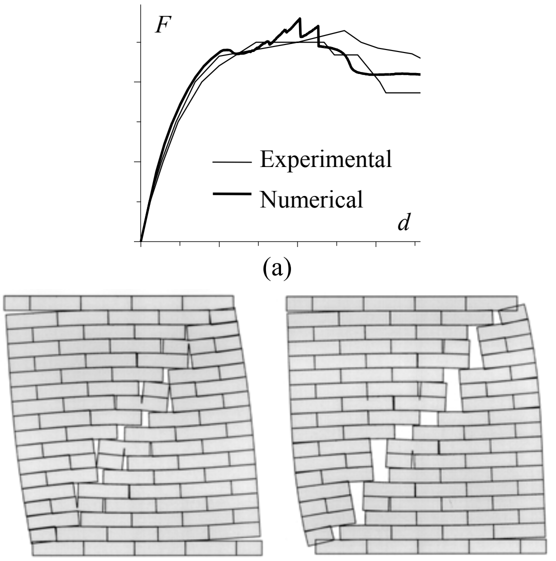
4.1 *Discontinuum models (Micro-modeling)*

Masonry joints act as planes of weakness and the explicit representation of the joints and units in a numerical model seems a logical step towards a rigorous analysis tool. This kind of analysis is particularly adequate for small structures, subjected to states of stress and strain strongly heterogeneous, and demands the knowledge of each of the constituents of masonry (unit and mortar) as well as the interface. In terms of modeling, all the non-linear behavior can be concentrated in the joints and in straight potential vertical cracks in the centerline of all units. In general, a higher computational effort ensues, so this approach still has a wider application in research and in small models for localized analysis. Applications can be carried out using finite elements, discrete elements or limit analysis.

The salient characteristics of discrete elements are: (a) rigid or deformable (combined with the finite element method) blocks; (b) connection between vertexes and sides / faces; (c) interpenetration possible, integration of the equation of motion (explicit formulation); (d) real damping coefficient (dynamic problem) or artificially high damping (static solution). The main advantages of the technique are adequate formulation for large displacements (contact update), and independent meshes for each deformable block. The main disadvantages are that a high number of contact points is needed for accurate representation of tractions in the interface, and the time requirements are rather high for large meshes, namely for 3D problems.

The salient characteristics of limit analysis are: (a) rigid blocks; (b) interpenetration not allowed; (c) mathematical formulation that leads to an optimization problem (linear or non-linear). The main advantages of the technique are adequate formulation for design problems (requires a low number of parameters) and fast analysis. The main advantages are that only the collapse load and mechanism can be obtained, tensile strength cannot be included in the analysis, and the introduction of the loading history remains a challenge.

A complete micro-model must include all the failure mechanisms of masonry, namely, cracking of joints, sliding over one head or bed joint, cracking of the units and crushing of masonry, as in Lourenço & Rots (1997) and Oliveira & Lourenço (2004). Figure 10 shows the results of modeling a shear wall with an initial vertical pre-compression pressure. The horizontal force F drives the wall to failure, keeping the top and bottom boundaries fully constrained, and produces a horizontal displacement d at top. Initially, two horizontal cracks develop at the top and bottom of the wall but at failure a diagonal stepped crack and crushing of the compressed toes are found. A complete discussion of the numerical results has been given in (Lourenço & Rots 1997).

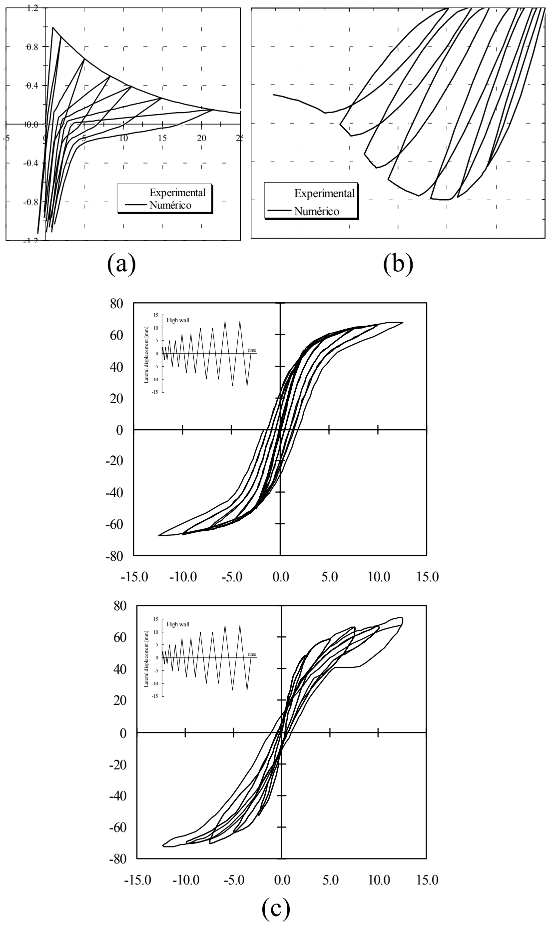


(a)

(b)

Figure 10. Results for an analysis of a shear wall (micro-modeling): (a) force-displacement diagram and (b) deformed meshes at peak and ultimate load.

The extension of the above model to include cyclic behavior is given in Oliveira & Lourenço (2004). To include non-linear unloading/reloading behavior in an accurate fashion, new yield surfaces are introduced in the above monotonic model. In the proposed model, the motion of the unloading surfaces is controlled by a mixed hardening law. By adopting appropriate evolution rules, it is possible to reproduce non-linear behavior during unloading, see Figure 11. The recent experimental work in the cyclic behavior of interfaces described in the previous chapter has shown some important characteristics, namely stiffness degradation in both tension and compression regimes, residual relative displacements at zero stress, absence of stiffness degradation in direct shear, and complete crack closing under compressive loading. The available experimental results concerning the cyclic behavior of interfaces suggest that: (a) Elastic behavior constitutes a satisfactory approach for shear unloading/reloading behavior; (b) Elastic unloading/reloading is not an appropriate hypothesis for tensile and compressive loading since observed experimental behavior cannot be simulated accurately, namely stiffness degradation and crack closing/reopening, which clearly exhibit non-linear behavior.



(a) (b)

(c)

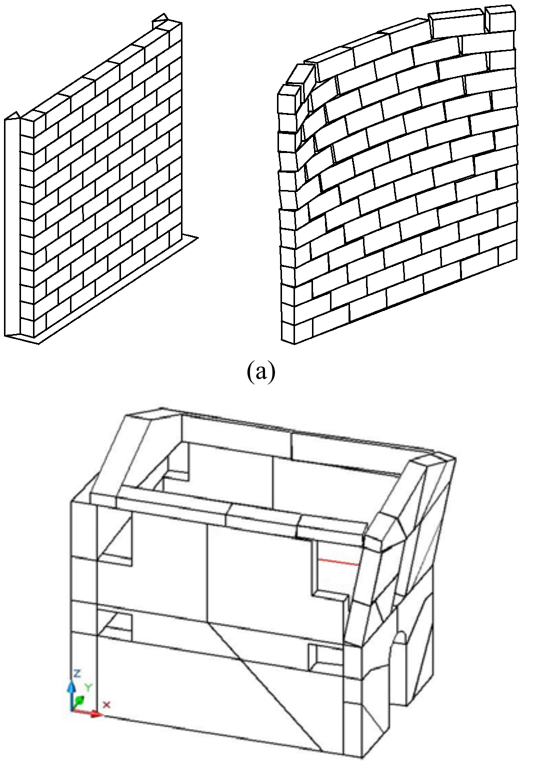
Figure 11. Experimental vs. numerical behavior for an interface model extended to cyclic formulation: (a) tension-compression behavior, (b) compression behavior and (c) shear walls (numerical results on the bottom).

The drawback of using non-linear finite element analysis in practical situations might include: (a) requirement of adequate knowledge of sophisticated non-linear processes and advanced solution techniques by the practitioner; (b) comprehensive mechanical characterization of the materials; and (c) large time requirements for the construction of the finite element model, for performing the analyses themselves and for reaching proper understanding of the results significance.

Limit analysis combines, on one hand, sufficient insight into collapse mechanisms, ultimate stress distributions (at least on critical sections) and load capacities, and on the other hand, simplicity to be cast into a practical computational tool. In addition, the number of necessary material parameters is low. The design of strengthening is an issue apart from analysis. FEM analysis can be mostly regarded as an assessment tool whereas limit analysis, cast into a practical computational tool, seems to allow easy calculations of strengthening provisions.

The applicability of limit analysis theory to unreinforced masonry structures modeled as assemblages of rigid blocks interacting through joints depends on some basic hypotheses. The first hypothesis is that the limit load occurs at small overall displacements, which is reasonable for most cases. The second hypothesis is that masonry has no tensile strength. The low tensile strength and the quasi-brittle tensile failure of masonry justify this assumption. The third hypothesis is that the shear failure at the joints is perfectly plastic, which is confirmed by experimental results.

Figure 12 illustrates results using advanced solution procedures for non-linear optimization problems, with a constitutive model that incorporates non-associated flow at the joints and a novel formulation for torsion, Orduña & Lourenço (2005a,b)



(a)

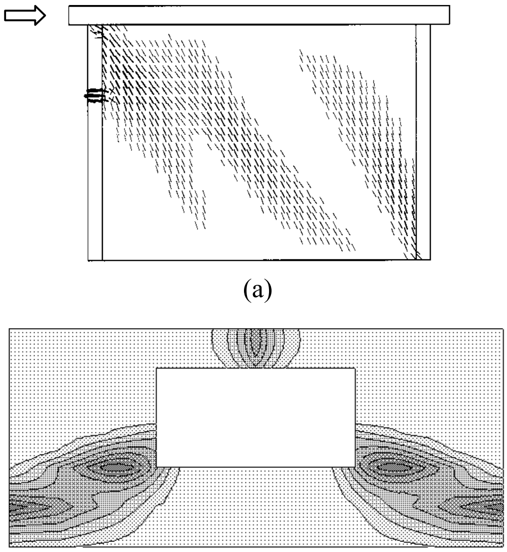
(b)

Figure 12. Results for different analyses (micro-modeling, using limit analysis): (a) panel subjected to out-of-plane failure and (b) simplified analysis of a complete building with macro-blocks.

4.2 *Finite element models for continua (Macro-modeling)*

Difficulties of conceiving and implementing macro-models for the analysis of masonry structures arise due to the fact that almost no comprehensive experimental results are available, but also due to the intrinsic complexity of formulating anisotropic inelastic behavior. Only a reduced number of authors tried to develop specific models for the analysis of masonry structures, always using the finite element method. Formulations of isotropic quasi-brittle materials behavior consider, generally, different inelastic criteria for tension and compression. The model introduced in Lourenço et al. (1998) and extended to accommodate shell behavior (Lourenço 2000), combines the advantages of modern plasticity concepts with a powerful representation of anisotropic material behavior, which includes different hardening/softening behavior along each material axis.

Figure 13 shows the results of modeling a shear wall with an initial vertical pre-compression pressure and a wall panel subjected to out of plane failure.



(a)

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Figure 13. Results for different analyses (macro-modeling: (a) shear wall and (b) panel subjected to out-of-plane failure.

4.3 *Application of macro-modeling to the protection of Lisbon – Munro Prize 2004*

Seismic analysis and vulnerability of historical city centers is a key issue for the preservation of the built heritage, for the safety of the population and for economical reasons. In particular, preservation of the built heritage with cultural value is considered a fundamental issue in the cultural life of modern societies. In addition to their historical interest, cultural heritage buildings are valuable because they contribute significantly to the economy by providing key attractions, in a context where tourism and leisure are major industries in the 3rd millennium. The need of preserving historical constructions is thus not only a cultural requirement but also an economical and developmental demand.

The study of historical constructions must be undertaken from an approach based on the use of modern technologies and science. It is the responsibility of the specialists to select and adequately manage the possible technical means needed to attain the required understanding of the morphology and the structural behavior of the construction and to characterize its repair needs. Modern requirements for an intervention include reversibility, unobtrusiveness, minimum repair and respect of the original construction, as well the obvious functional and structural requirements. Unfortunately, several historical constructions suffered partial or total collapse in the course of times due to earthquakes, fatigue, deterioration, soil movements or the lack of structural understanding of the original constructors, being earthquakes the most destructive action. These losses are simply not quantifiable in economic terms, as neither lives nor cultural heritage can be reinstated by post-earthquake reconstruction plans.

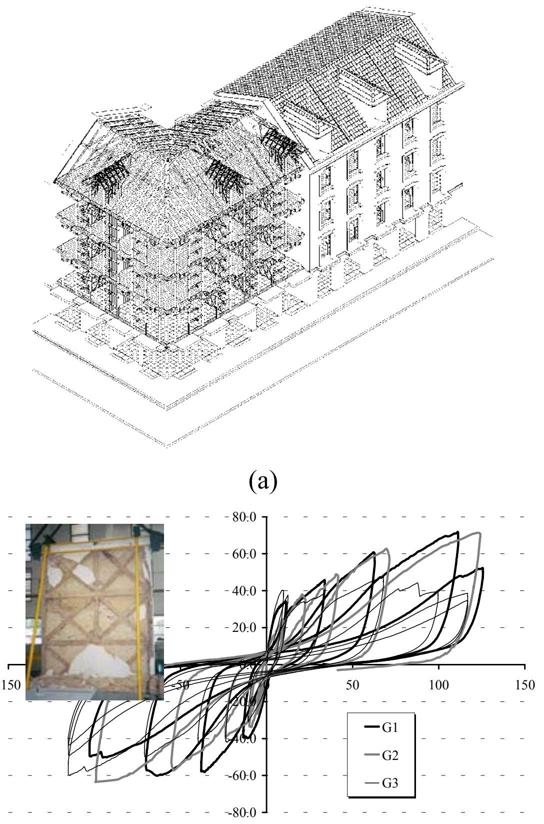
In 2003, 380 natural and human based catastrophes caused 60,000 casualties, being 43,000 caused by earthquakes alone, and a total economic loss of 70,000 million euro. In December 26, 2004, a single earthquake off the West Coast of Northern Sumatra and subsequent tsunami resulted in over 280,000 people killed and over 1.1 million displaced in 10 countries from South Asia and East Africa. This exceptional event caused an estimated economic loss over 20,000 million euro.

The need to better understand the behavior of existing buildings drove the present paper, which presents a specific case study: the eighteenth century downtown part of Lisbon, Portugal. This part of Lisbon is usually denoted as “Pombaline”, after Marquis of Pombal that was the coordinator of the reconstruction works, has been built after a major earthquake, followed by a tsunami and a large fire, on November 1, 1755. Of a Lisbon population of 275,000, up to 90,000 were killed, with another 10,000 killed across the Mediterranean in Morocco. Eighty-five percent of Lisbon's buildings were destroyed, including famous palaces and libraries. The original concept of Pombaline buildings aimed at providing strength to horizontal loading and capacity to dissipate energy. Among the features of the construction system, the so-called “gaiola”, i.e. cage, stands out. The cage consists of a set of timber members embedded along the inner face of the main stone masonry facade walls. Then, ashlars placed around the door and window openings are tied against this internal timber grid, by means of iron cross ties. Additional bracing is provided by the timber floors, which possess some diaphragm action enhanced by iron ties, bolted to the floor beams and deeply embedded in masonry main walls, and by timber connectors, nailed to the above mentioned timber grid and also embedded in the masonry. The confined facade piers are then connected to a bi-directional vertical bracing system of timber-framed walls, with light ceramic and rubble masonry infill. The term “gaiola” was coined because the building seemed like a big cage, with the carpentry work high up in the air, generally some floors ahead of the masons.

The conservation of historical city centers in seismic areas requires a strategic plan and proper methodology including aspects such as: Phase 1 – Preliminary investigation, interpretation of historical documentation and understanding the historical context, and appraisal of the general structural characteristics of the construction; Phase 2 – Full diagnosis, making use of selected non-destructive testing and numerical analyses; Phase 3 – Designing of structural modifications, according to the requirements of safety, upgrading, compatibility and durability, as well as the modern principles of action in the built heritage such as reversibility, unobtrusiveness and minimum modification; Phase 4 – Carrying out the works with proper quality assurance and qualified workers; Phase 5 – Monitoring, as an evaluation of the effects associated with the modifications. The approach of combining conservation requirements with safety, within the restoration of historical city centers is, often, still not an obvious requirement for policy makers. Therefore, it is necessary to develop “Codes of practice” that contain all available information on local seismic activity, original construction techniques and precarious situations, suggesting methods of validation of the proposed structural modifications and helping those responsible for planning the actual site works to select adequate and efficient techniques, which respect the local culture and limit future damage.

The Munro Prize paper, Ramos & Lourenço (2004) focus on Phase 2 referred above. The finite element method was adopted for a number of different analyses, introducing non-linear behavior of the materials. From the analysis, the following issues have been addressed: (a) seismic vulnerability of this type of constructions; (b) influence of the group of buildings on the seismic behavior of the individual buildings that compose a single compound; (c) methodology for action. It is believed that the conclusions obtained with respect to the seismic assessment of masonry buildings can be extrapolated for the wide variety of historical city centers.

Figure 14 presents the typical external and internal constitution of Pombaline buildings, together with tests in real size composite timber-masonry walls removed from one of the buildings.

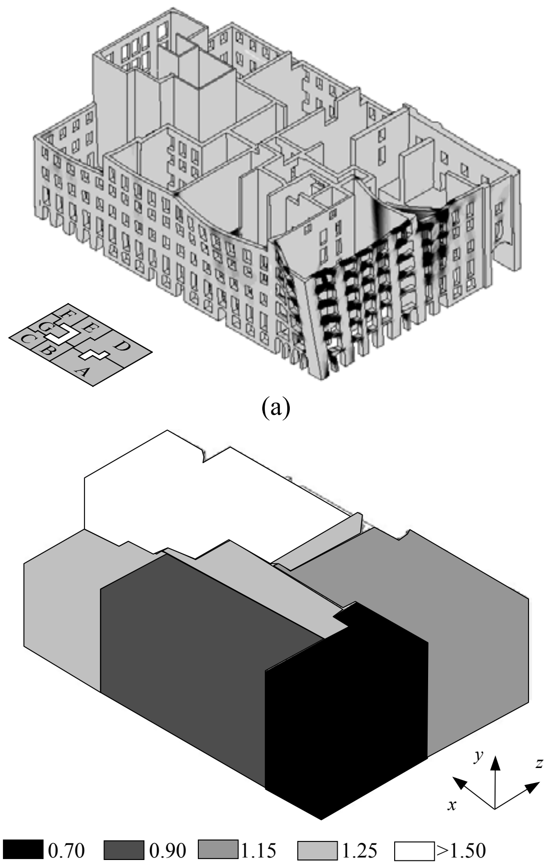


(a)

(b)

Figure 14. Aspects of Pombaline construction: (a) building with the façade walls removed to show the timber bracing system and (b) mechanical characterization of the internal walls under combined in-plane vertical and horizontal loading.

Figure 15 shows selected results of the numerical simulation aiming at discussing seismic vulnerability. The full model is rather complex from the geometrical and material points of view, comprising 8,820 elements with 57,267 nodes, totaling approximately 160,000 degrees of freedom. Five loading combinations were applied: one corresponding to the prescribed vertical loads, and four load combinations for horizontal actions, associated with the seismic action acting along the main directions of the compound. Six man-months were required for creating the mesh and performing the five non-linear analyses. Non-linear behavior was adopted for all elements, with the exception of the concrete and composite slabs that were assumed linear elastic throughout the analysis. In fact, the slabs were considered in the model only to simplify the definition of loads and to introduce a rigid diaphragmatic effect for the seismic analysis.



(a)

(b)

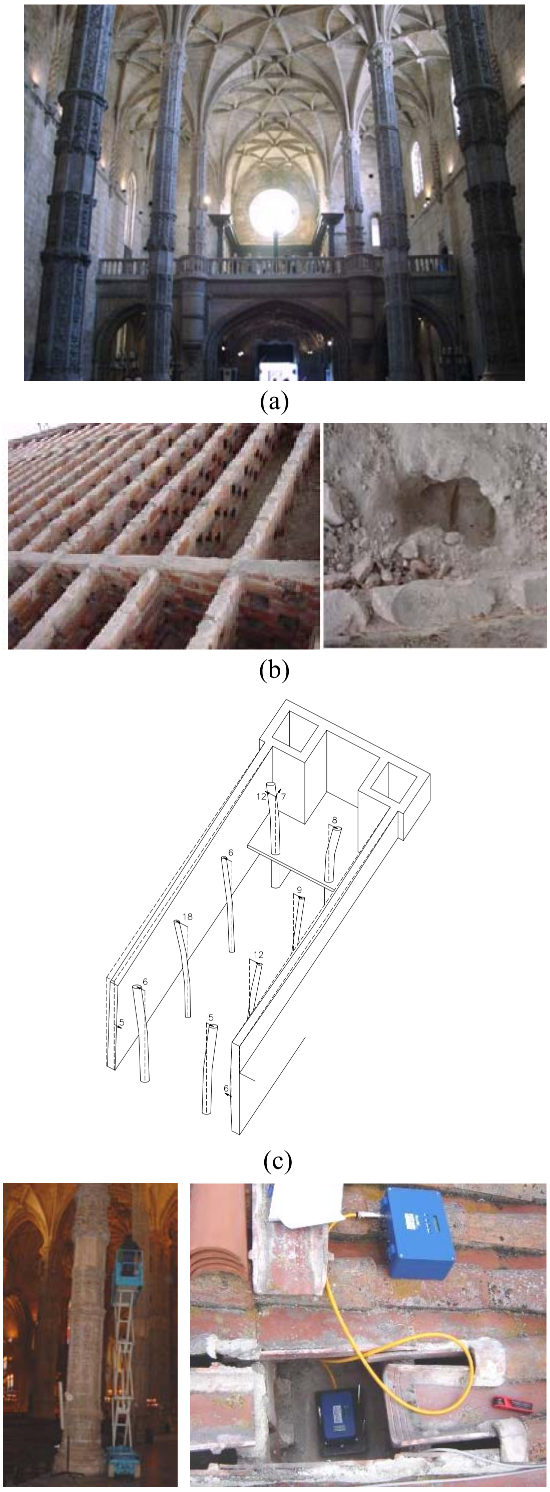
Figure 15. Results obtained for the numerical simulations: (a) cracking pattern and deformed mesh in the full block for a horizontal seismic action in –z axis (contour of maximum principal strains) and (b) seismic vulnerability map of the block, given by the calculated safety factors after successive analysis of the block with removal of collapsed buildings.

5 EU-INDIA CONTRACT “IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS”

The main objective of this project is the development of a social and economic argument, at Indian-European level, to support an earthquake protection innovative program for cultural heritage masonry buildings at risk. This will consider cultural heritage buildings / monuments in an earthquake prone area in India, identify seismic input scenarios and specific vulnerability features, produce a risk analysis with respect to different return periods, and study advanced upgrading and strengthening techniques. The Plan of Action is based on a multidisciplinary approach, entailing aspects of risk analysis, in situ survey and monitoring, numerical analyses and the design/application of innovative strengthening strategies. The objective is to devise strengthening strategies that, based on thorough knowledge of the traditional craft and material, can use modern materials and techniques to prevent vibration borne damage to the structures and to the decorative apparatus. The project is lead by University of Minho, with the partnership of Central Building Research Institute (India), Polytechnic University of Barcelona (Spain) and University of Padova (Italy).

As a part of the project, four case studies have been selected for detailed study and monitoring. In Portugal, Monastery of Jerónimos, Lisbon, has been adopted as case study. Monastery of Jerónimos is, probably, the crown asset of Portuguese architectural heritage dating from the 16th century. The monumental compound has considerable dimensions in plan, more than 300 × 50 m^2, and an average height of 20 m (50 m in the towers). The monastery evolves around two courts. The construction resisted well to the earthquake of November 1, 1755. Later, in December 1756, a new earthquake collapsed one column of the church that supported the vaults of the nave and resulted in partial ruin of the nave. In this occasion also the vault of the high choir of the church partially collapsed.

Examples of the works already carried in this case study are shown in Figure 16 and Figure 17. This includes historic and geometrical survey, condition survey, a combination of non-destructive testing techniques, advanced simulation using non-linear finite elements and installation of remote controlled long-term static and dynamic monitoring systems.


(a)

(b)

(c)

(d)

Figure 16. Monastery of Jerónimos: (a) view of the nave and choir (b) inspection of the vault nave; (c) survey of the columns; (d) radar inspection and ambient vibration acquisition.

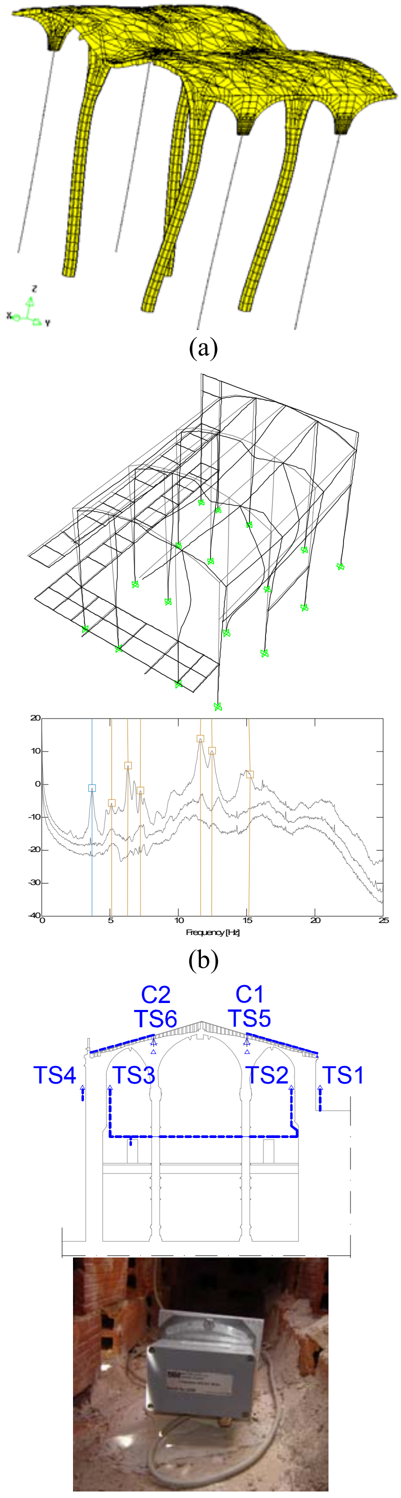


Figure 17. Monastery of Jerónimos: (a) structural analysis of the nave, (b) dynamic identification with frequency domain decomposition and (c) static monitoring system.

6 CONCLUSIONS

Significant knowledge is available in the context of modern testing and advanced analysis of masonry structures. Constraints to be considered in the use of advanced modeling are the cost, the need of an experienced user / engineer, the level of accuracy required, the availability of input data, the need for validation and the use of the results. Obtained results are usually important for understanding the structural behavior of the constructions. But, as a rule, advanced modeling is only necessary in practice to understand the behavior and damage of (complex) constructions and to assist in the definition of rational safety assessment rules, based on a reliable and economical numerical laboratory. The key message of the paper is that research and innovation are strongly needed to assess the vulnerability of existing constructions and to define economical rational design rules. Without this, the ancient household and the preservation of the architectural heritage remain at risk.

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