Reducing the seismic vulnerability of cultural heritage buildings

Paulo B. Lourenço[1], Pere Roca[2], Claudio Modena[3] and Daniel V. Oliveira[1]

[1] University of Minho. Portugal
[2] Technical University of Catalonia. Spain
[3] University of Padova. Italy

Key words: immovable heritage, seismic protection, simplified methods, case study, dissemination

1 Introduction

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 centres 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, this paper focus on a research project funded under the EU-India Economic Cross Cultural Programme from the European Commission. The partners involved in the project are University of Minho (coordinating institution), Portugal, Technical University of Catalonia, Spain, Central Building Research Institute, India, and University of Padova, Italy.

2 Objectives and activities

The main objective of the 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, and study advanced upgrading and strengthening techniques, based on four case studies (see Figure 1). 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 proposal mainly focuses on:

- The identification of preventative measures that can be implemented to improve the earthquake resistance of historic masonry Cultural/Historical Buildings (CHBs) and Cultural Heritage in general;
- Definition and application of optimal modelling strategies for determining the load bearing capacity of historic structures before and after repair;

- Cost/benefit analysis of the proposed procedures taking into account the different levels of complexity and of disposable budget;
- Set up of a comprehensive database of traditional local technologies for construction and repair;
- Full conservation design for three case studies selected in Europe and India;
- The interchange of knowledge between European and Indian experts.

This implies a better understanding and enhancement of their inherent earthquake-resistant characteristics of CHBs achieved through compared vulnerability analysis, in situ monitoring of real cases and numerical simulation.

(a)

(b)

(d)

(c)

Figure 1: Case studies: (a) Monastery of Jerónimos, Lisbon, Portugal – World Heritage Monument; (b) Cathedral of Majorca, Spain; (c) Qutub Minar, New Delhi, India – World Heritage Site; (d) Cathedral of Reggio Emilia .

The activities included in the project are:

- Activity 1: Inventory of monuments at risk. The aim of this activity of to develop, at a European-Indian level, the social and economic argument to support an earthquake protection program for monuments at risk and to collect existing background information on the three case studies. This activity includes the creation of an inventory of monuments at risk from earthquakes in Portugal, Spain, Italy and India. From the inventory, a selection of about 40 monuments (10 per country) will be selected on the basis of available geometrical data, historic and architectural significance, importance to local visitor economy, seismicity of the area and seismic vulnerability according to simplified methods (ratio between walls area and total area; ratio between weight and total area; shear base action).

- Activity 2: Seismic activity evaluation and site effects. The aim of this activity is to evaluate the seismic hazard and the site effects associated with each church of a selected collection. For the hazard evaluation, information will be gathered on hazard studies, in the various countries where the monuments are located. The information is to be analyzed, in order to homogenize the different patterns in the data treatment and establish comparisons among different sites and categories the situations in terms of high, medium and low hazard.
- Activity 3: Conference in Padova, Italy. The fourth international conference on structural analysis of historical constructions – possibilities of experimental and numerical techniques was carried out during November 2004, with the participation of 350 delegates.
- Activity 4: In situ tests and monitoring. The objectives of this activity are: (a) To develop a monitoring system suitable for the identification of dynamic properties of monuments; (b) To identify, by means of long term vibration monitoring, the dynamic response of the five case studies to natural vibrations caused by traffic, wind and minor earthquakes occurring during the monitoring period; (c) To carry out a set of NDT tests to identify in situ the mechanic properties of the materials. In general the activity includes the design and production of a long-term monitoring system based on the use of fixed measurement devices placed at meaningful points of the structure, with continuous remote logging. The integrated monitoring system will include displacement transducers, crackmeters, tiltmeters, accelerometers, seismometers and wind and temperature transducers. The systems will be installed in the four case studies.
- Activity 5: Evaluation and design of strengthening. The objectives of the activity of to simulate the static and dynamic responses of the selected three ancient constructions, including degradation processes and repeated shaking. This will allow to (a) identify limit thresholds associated with accumulated permanent deformation; (b) identify the role of performance-related overall properties: dissipation, monolithism, ductility, and the extent to which they should be considered in the design of the strengthening strategies; (c) assess the sensitivity to material parameters. In addition, a European-Indian database of current strengthening strategies for monuments will be established, together with a measure of the efficiency of strengthening strategies in terms of reduced vulnerability with respect to the target limit state, but also in terms of respect of the conservation criteria. The activity includes the usage of methods for the analysis of large masonry buildings available at the partners, for the simulation of the actual condition of the structures analyzed and determine their main weak points, as well as their main needs of repair and retrofitting. In addition, different strengthening strategies for the case studies will be analyzed.
- Activity 6: Definition of guidelines. The objective of the activity is to provide guidelines for end users and professionals on the methodological approach to conservation of historic structures in seismic areas. These will include the general concepts and specifications, which must lead to adequate strengthening design. The guideline will include the definition of alternative strengthening techniques with respect of quantity and quality of implementation, alternative materials, and alternative implementation procedures.

- Activity 7: Dissemination. The objectives of this activity are the following: (a) To develop and maintain a web site with progress update of the project; (b) To set and update a database on multi-media support of structural information on historic buildings at risk in Europe and on strengthening techniques; (c) To organize a round robin for assessment of strengthening strategy; (d) To prepare a 3D virtual model. The findings will be presented and discussed with practitioners at purposely-organized workshops in the countries of each workshop. For one of the case studies and one specific strengthening strategy a 3D virtual model will be developed, with the following objectives: (a) Showing the building process and the structural changes through the centuries; (b) Explaining the flow of forces within the structure and link to a demo on the basic principles of structural behaviour of old structures; (c) Showing the collapse of the structure; (d) Showing how strengthening changes the flow of forces and that the new structure survives. The target audience will be visitors of the considered monument and the aim is to raise the profile of the problem and its possible solutions at European-Indian level.
- Activity 8: Conference in New Delhi, India. The fifth international conference on structural analysis of historical constructions – possibilities of experimental and numerical techniques is to be carried out in New Delhi, India, during 6-8 November 2006. This will provide a forum for the discussion of the results of the project and for full knowledge transfer for practitioners worldwide and, specifically, in India.

3 Highlights of available results

3.1 Simplified methods of analysis

An analysis of the damage survey of historical masonry buildings for the Umbria-Marche earthquake [1] shows that the problem of earthquake damage is generalized and that structural typologies, as well as associated types and distribution of damage, are fairly recurring. Seismic protection actions requires the knowledge of seismic site response, the definition of the seismic load (a rather challenging issue) and the knowledge of the characteristics of existing buildings. This is a gigantic task, requiring large funds and considerable large time-span, but efforts have been made to create damage scenarios and to prioritize retrofitting works, see Barbat et al. [2] and Langa and Bachmanna [3].

The approach adopted in the present project aims at a much more simple, fast and low cost procedure, being based on a simplified geometric approach for immediate screening of the large number of buildings at risk, see [4] for more deatils. The objective is to evaluate the possibility to adopt simple indexes related to geometrical data as a first (very fast) screening technique to define priority of further studies with respect to seismic vulnerability. These fast techniques are to be used without actually visiting the buildings, being therefore not accurate. It is expected that the geometrical indexes could detect cases in serious risk and, thus, define priority of additional studies in countries/locations without recent moderate or severe earthquakes The historical buildings considered at possible risk may deserve more detailed studies using advanced computer simulations, together with adequate material and structural characterization, see Lourenço [5] and ICOMOS [6] for recommendations. In case of urban areas, and in spite of the diversity, a common matrix can usually be established for the seismic areas, more structural than technological. This consists of low building height (up to three stories), moderate spans (maximum of four or five meters) and large thickness of the walls (less than 1/7 of the height), see Giuffrè [7].

The work carried out paper is focused in European churches, given: (a) Their intrinsic greater structural vulnerability due to open plan, greater height to width ratio and, often, the presence of thrusting horizontal structures from vaulted ceilings and timber roofs; (b) The ample geometry survey drawings and documentation available. Moreover, in earthquake prone countries, churches and monuments have already been subjected to earthquakes, and sometimes survived them, meaning that they are testimonies and they represent full-scale testing data. This fact, permits to discuss and, generally, to accept that these ancient structures have been adjusted to local seismicity. Forty-four churches from Portugal, Spain and Italy have been selected and analyzed considering three in-plane indexes and three out-of-plane indexes. The proposed indexes of monuments located in different seismic areas are compared with the respective seismic hazard, i.e. the peak ground acceleration (PGA), defined for a 10% probability of exceedance in 50 years for a rock-like soil, corresponding to a return period of 475 years. The recognition of the likely existence of a correlation between structural characteristics and seismic hazard is, therefore, sought.

The usage of simplified methods of analysis usually requires that the structure is regular and symmetric, that the floors act as rigid diaphragms and that the dominant collapse mode is in-plane shear failure of the walls. In general, these last two conditions are not verified by ancient masonry structures, meaning that simplified methods should not be understood as quantitative safety assessment but merely as a simple indicator of possible seismic performance of a building. The following simplified methods of analysis and corresponding indexes are considered:

In-plane indexes:

- Index 1: In-plan area ratio;
- Index 2: Area to weight ratio;
- Index 3: Base shear ratio.

Out-of-plane indexes:

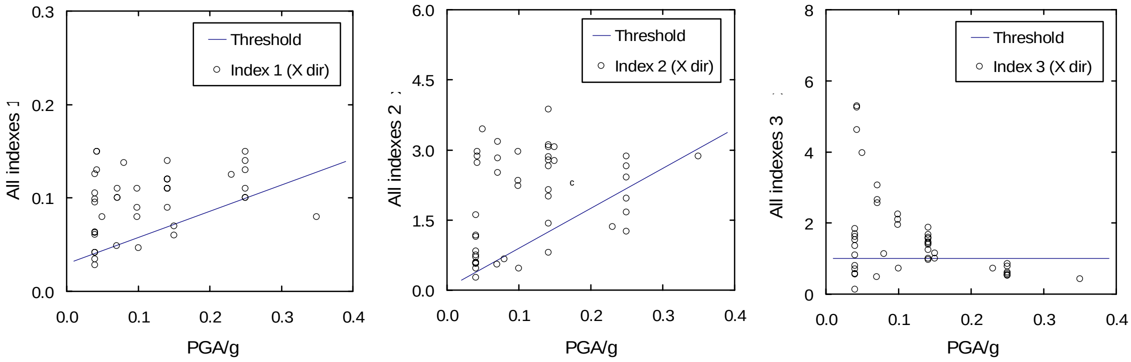
- Index 4: Slenderness ratio of columns;
- Index 5: Thickness to height ratio of columns;
- Index 6: Thickness to height ratio of perimeter walls.

These methods can be considered as an operator that manipulates the geometric values of the structural walls and columns and produces a scalar. As the methods measure different quantities, their application to a large sample of buildings contributes to further enlightening on their application. As afore-mentioned, a more rigorous assessment of the actual safety conditions of a building is necessary to have quantitative values and to define remedial measures, if necessary.

The investigation carried out includes the application of the simplified methods to a sample of forty-four monuments (19 Portuguese, 15 Spanish and 10 Italian), selected according to the seismic level and to the availability of information. This research pursues the following objectives: (a) Validate the hypothesis of an empirical relation of the ancient builders, able to define an expedite preliminary assessment of seismic vulnerability of historical masonry buildings; (b) Validate the hypothesis of an empirical relation between architectural-structural characteristics of historical masonry buildings and seismicity; (c) Prioritize further investigations and possible remedial measures for the selected sample; (d) Extrapolate, from the results on the sample, the seismic vulnerability of ancient masonry buildings in those countries.

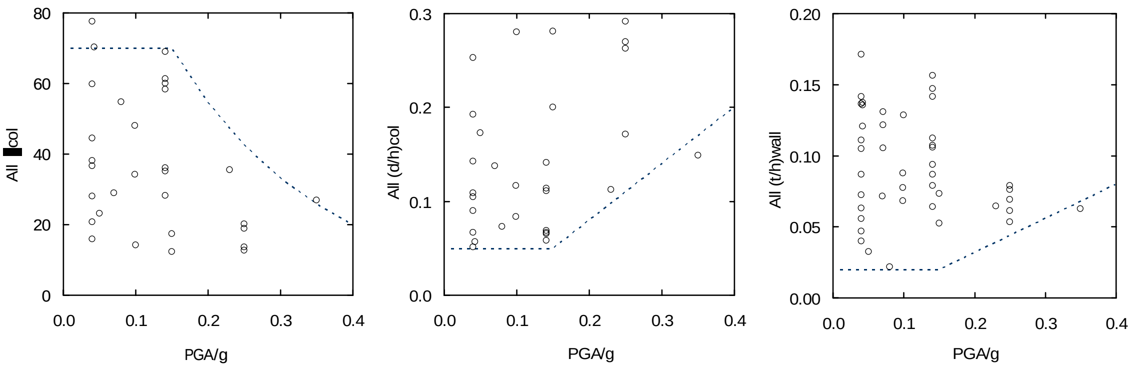
The values computed for the three in-plane indexes and the three out-of-plane indexes, which can be found elsewhere [8], are graphically represented in Figure 2, for the entire sample and for the transversal direction, and in Figure 3, for the entire sample , as a function of the local parameter PGA/g.

A proposal for the usage of simplified methods was made, taking into consideration the simultaneous violation of two or three of the in-plane indexes. The results show the need for deeper investigations ranges between 18% and 43% of the sample (8 and 19 churches, respectively), see [8] for details. The analysis of the out-of-plane indexes shows that a logical common trend can be established. For low and moderate seismicity, indexes do not exhibit a dependency on seismicity. However, for increasing seismicity, they tend to vary in a logical pattern. Furthermore, the observed trend allowed the proposal of possible threshold criteria for each of the indexes.



(a) (b) (c)

Figure 2: Relationship between in-plane indexes (transversal direction of the church) and PGA/g, for the entire sample: (a) index 1, (b) index 2, (c) index 3.



(a) (b) (c)

Figure 3: Relationship between out-of-plane indexes and PGA/g, for the entire sample: (a) index 4; (b) index 5; (c) index 6.

3.2 Case study – Monastery of Jerónimos, Portugal

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.

The Gothic style was lately introduced in Portugal, incorporating a specific national influence. The so-called “Manueline” style (after King D. Manuel I), exhibits a large variety of architectural influences and erudite motives. An interesting aspect appears in the 16th century, when the traditional three naves churches start to be replaced by a configuration with small difference in height for the naves. Here, the vault springs from one external wall to the other, supported in slender columns that divide almost imperceptibly the naves. From the traditional art, only the proportions and roof remain, being the concepts of space and structure novel. The fusion of the naves in the present Church, see Figure 4, is more obvious than in other manifestations of spatial Gothic. For this purpose, arches are no longer visible, the slightly curved vault comprises a set of ribs and the fan columns reduce effectively the free span. Additional information about the church and the vault can be found in [9].

(a) (b) (c)

Figure 4: Church of Monastery of Jerónimos: (a) half of transversal cross-section; (b) vault and choir; and (c) aspect of the three naves.

The church has considerable dimensions, namely a length of 70 m, a width of 40 m and a height of 24 m. The plan includes a single bell tower (south side), a single nave, a transept, the chancel and two lateral chapels. In order to assess the safety of the church, several in situ tests have been carried out: (a) three-dimensional survey of the church; (b) sonic and GPR tests in the columns to assess the integrity; (c) radar investigation to detect the thickness of the masonry infill in the vault and pier [10]; (d) removal of the roof, visual inspection, bore drilling, metal detection and chemical analysis of materials [11]; (e) dynamic identification, see Figure 5 for examples.

Advanced structural analysis was considered in order to quantify the seismic vulnerability. Different models have been used to study the behaviour of the compound and of the church, see Figure 6. In the complete model of the compound only the very large openings were considered. The geometry of the model was referred to the average surfaces of the elements. All the walls, columns, buttresses, vaults and towers were included in the model, with the exception of a few minor elements. 7. The finite element mesh is predominantly rectangular and structured, but, for the towers and local refinements, triangular finite elements are also adopted. All elements possess quadratic displacement fields. The mesh includes around 8000 elements, 23500 nodes and 135000 degrees of freedom. The time necessary for total mesh generation, including definition of supports, loads and thicknesses, can be estimated in three months. A push-over analysis with zero tensile strength indicated that the towers of the Museum are the critical structural elements featuring displacements of around 0.10 m in each case and cracks of around 0.01 m. Smaller cracks are also visible in the church. The analyses inidcate that the monastery is a safe construction, with respect to the wall behaviour. As the vaults were not properly considered, a conclusion regarding the safety of the vaults (thus, of the church) is impossible.

In order to better study the church, a more refined model was adopted for the main nave, including the structural detail representative of the vault and more unfavourable. Appropriate symmetry boundary conditions have been incorporated. Therefore, the model represents adequately the collapse of the central-south part of the nave. The model includes three-dimensional volume elements, for the ribs and columns, and curved shell elements, for the infill and stones slabs. The external (south) wall was represented by beam elements, properly tied to the volume elements. The supports are fully restrained, being rotations possible given the non-linear material behaviour assumed. All elements have quadratic interpolation, resulting in a mesh with 33335 degrees of freedom.

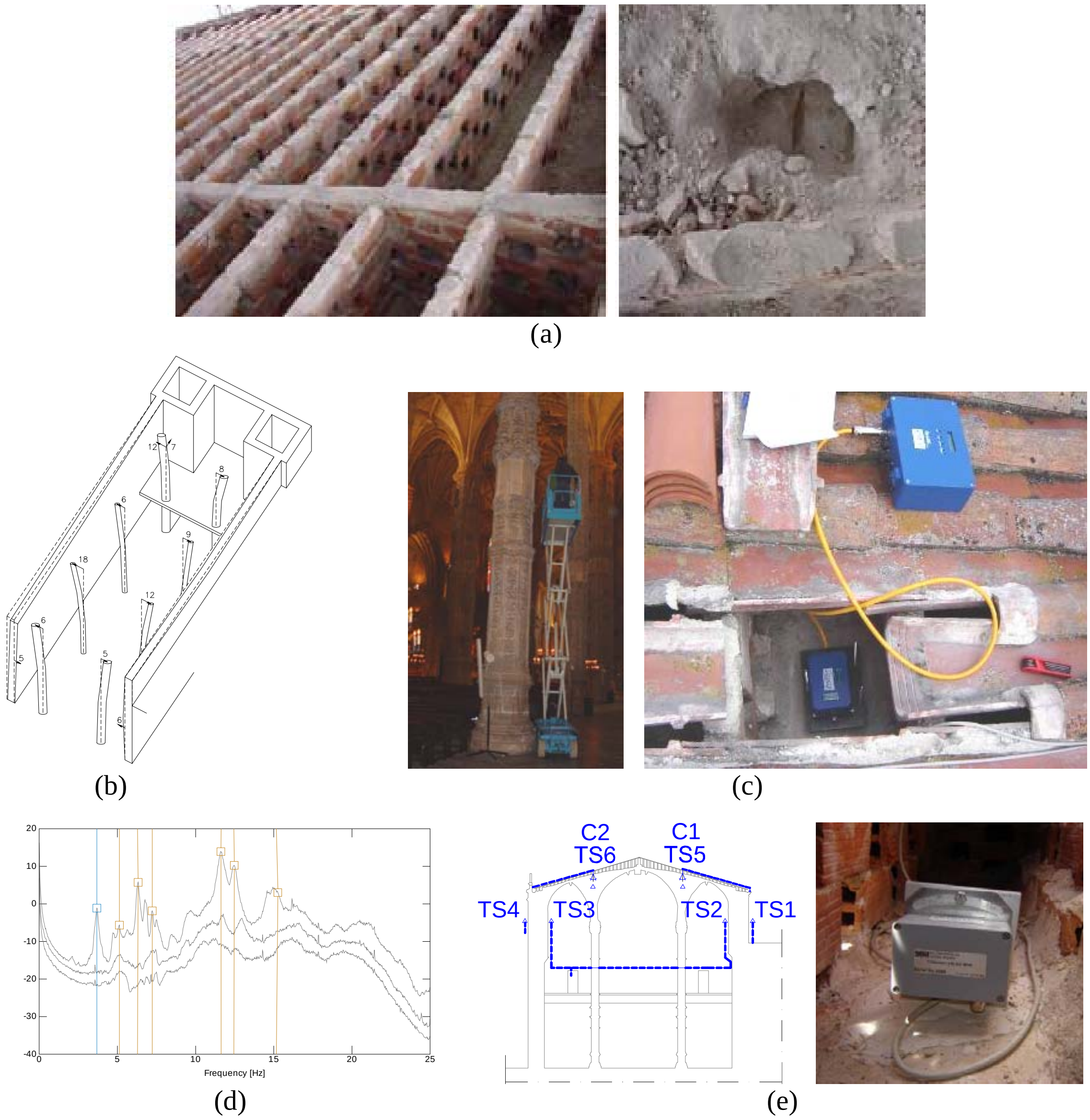
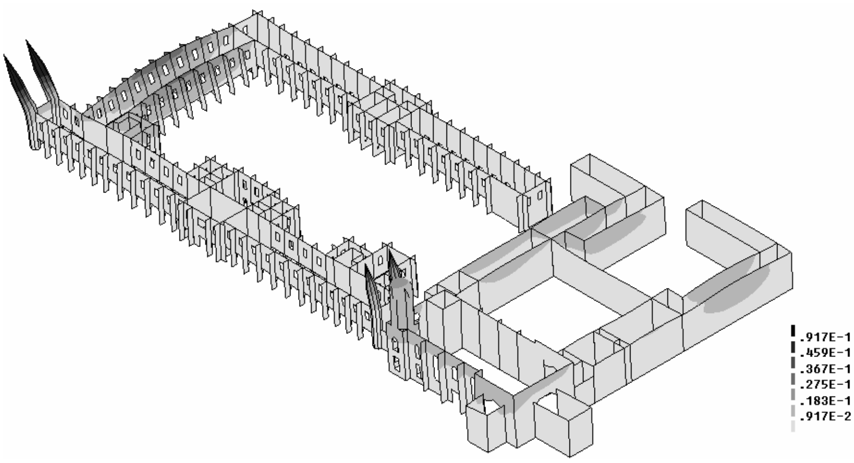
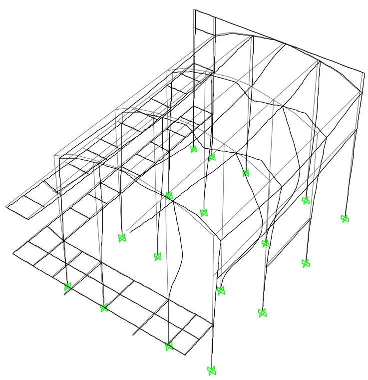


Figure 5: In situ testing and monitoring for Monastery of Jerónimos: (a) inspection of the vault nave; (b) survey of the columns; (c) radar inspection and ambient vibration acquisition; (d) dynamic identification; (e) static and dynamic monitoring.

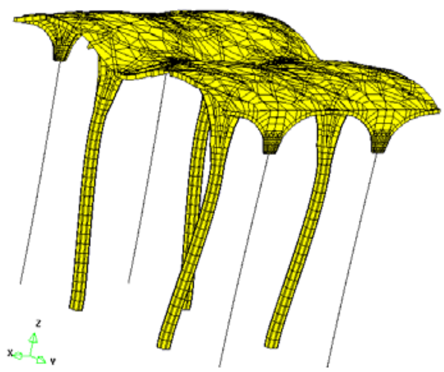
Fig. 6d illustrates the load-displacement diagrams for the vault key and top of the column. Here, the load factor represents the ratio between the self-weight of the structure and the applied load, meaning that the ultimate load factor is equivalent to the safety factor of the structure. It is possible to observe that the response of the structure is severely nonlinear from the beginning of loading, for the nave, and from a load factor of 1.5, for the column. The behaviour of the nave is justified by the rather high tensile stresses found in the ribs, using a linear elastic model. The collapse of the columns is due to the normal and flexural action. The safety factor is 2.0, which is low for this type of structures. The stresses are bounded in tension and compression, meaning that cracking and crushing occurs. The pairs of transverse ribs that connect the columns (in the central part of the structure) exhibit significant cracking, as well as the infill in the same area. Additional cracking, less exuberant and more diffused, appears in the central octagon defined by the capitals of the four columns. Such cracking occurs at the key of the octagon and in the longitudinal ribs, which confirms the larger displacements of the vault and the bidirectional behaviour of the vault.



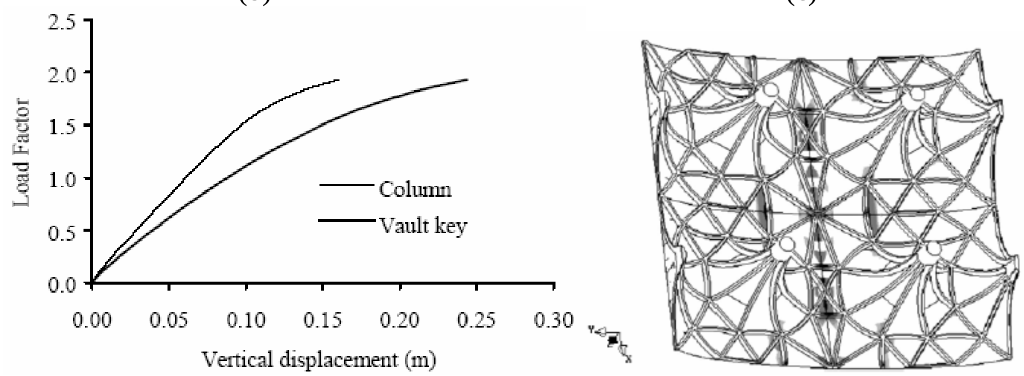
(a)



(b)



(c)



(d)

Figure 6: Structural analysis for Monastery of Jerónimos: (a) push-over analysis of compound; (b) model updating and dynamic time integration of church; (c) detailed analysis of nave; (d) results for the detailed analysis of the nave in terms of displacements and crack widths.

4 Conclusions

The European Dimension of the project is clear as Europe is a leader in the generation of knowledge, methodology and technology applicable to the conservation and restoration of the architectural heritage. Equipments and research cannot be usually funded in one country and require a strong collaboration between the scientific organisms of each country, as carried out in the project. Moreover, seismic activity extends well to a wide range of countries in Europe, of particular severity in the Mediterranean basin.

The most important novelty of the programme is its integrated approach, which will use forefront developments in seismic and conservation engineering, innovative research and

technology, to tackle the problem of improving the capacity of masonry cultural heritage buildings of significant value to resist to dynamic actions. This is made possible by the high level of international expertise in each of these fields that the partners have been ready to share.
The impact of the project is rather high with respect to the scientific and technical communities, with 18 papers in national and international conferences, 4 MSc and 4 PhD Theses, and 2 conference proceedings. Three workshops with senior officers of local and national heritage authorities have been held in Italy (2004), India (2005) and Portugal (2006). In addition, 3 news about the project appeared in daily newspapers in India. Dissemination will be further extended with a DVD freely distributed in the end of the project, including: (a) A database on multi-media support of structural information on the 54 monuments in Europe and India; (b) A 15 minutes DVD professional video of the project; (c) Design and validation of monitoring systems and sensors; (d) State of the art for remedial techniques in historical structures, including a comprehensive discussion on the case studies and a benchmark on dynamic identification techniques and advanced structural analysis; (e) Guidelines for seismic strengthening of historical structures; (f) Development of a 3D virtual model for Qutub Minar, including building process, flow of forces, possible structural collapse and strengthening.

5 European Project Details and Acknowledgment

Contract No. ALA-95-23-2003-077-122, Title: Improving the seismic resistance of cultural heritage buildings, Co-ordinator: Paulo B. Lourenço, Affiliation: University of Minho, Portugal. The authors gratefully acknowledge the support of the European-Indian Economic Cross Cultural Programme, under this contract.

6 References

[1] GNDT, *Seismic damage and vulnerability of the churches in Umbria (in Italian)*, CD-ROM, Presidency from the Italian Ministry Council, 1998.
[2] Barbat, A., Yépez, F., Canas, J., 'Damage scenarios simulation for seismic risk assessment in urban zones', *Earthquake Spectra*, 12(3), 1996, pp. 371-394.
[3] Langa, K., Bachmanna, H., 'On the seismic vulnerability of existing buildings: A case study of the city of Basel', *Earthquake Spectra*, 20(1), 2004, pp. 43-66.
[4] Lourenço, P.B., Roque, J.A., 'Simplified indexes for the seismic vulnerability of ancient masonry buildings', *Construction and Building Materials*, 20(4), 2006, pp. 200-208.
[5] Lourenço, P.B., 'Computations of historical masonry constructions', *Progress in Structural Engineering and Materials*, 4(3), 2002, pp. 301-319.
[6] ICOMOS, 2001, *Recommendations for the analysis, conservation and structural restoration of architectural heritage*.
[7] Giuffrè, A., Seismic damage in historic town centers and attenuation criteria, Annali di Geofisica, 38(5-6), 1995, pp. 837-843.
[8] University of Minho, *Overview of seismic risk for large span buildings heritage,* Report elaborated under contract ALA/95/23/2003/077-122, "Improving the Seismic Resistance of Cultural Heritage Buildings", Guimarães, Portugal, 2005.
[9] Genin, S.M., 'The nave vault of the Hieronymites Monastery Church in Lisbon' in *Proceedings of Historical Constructions 2001*, Lourenço, P.B. and Roca, P., (eds.), University do Minho, Guimarães, 2001, pp. 293-302.
[10] Oliveira, M.M.P., *Radar investigation of the Church of Jerónimos* (in Portuguese), Report 177/2002, Laboratório Nacional de Engenharia Civil, Lisbon, Portugal, 2002.
[11] Mun, M., *Study of the constitution of the vaults in the Church from the Monastery of Jerónimos using radar and complementary diagnosis methods* (in Portuguese), Report 176/2002, Laboratório Nacional de Engenharia Civil, Lisbon, Portugal, 2002.
[12] Lourenço, P.B., Krakowiak, K.J., Fernandes, F.M., Ramos, L.F., 'Failure analysis of Monastery of Jerónimos, Lisbon: How to learn from sophisticated numerical models?', *Engineering Failure Analysis*, 2006, accepted for publication.