1. LA RESISTENCIA SÍSMICA DE ESTRUCTURAS DE MAMPOSTERÍA: COMPORTAMIENTO EXPERIMENTAL, POSIBILIDADES DE ANÁLISIS Y CASOS DE ESTUDIO

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RESUMEN

La conservación y restauro de estructuras históricas representa aun un desafío para los proyectistas de hoy no obstante los avances importantes que ocurrieran en las últimas décadas, sea con respecto a ensayos no-destructivos, caracterización mecánica, herramientas para análisis estructural, y conocimiento en materiales y técnicas tradicionales, y materiales y técnicas innovadoras. Se presenta una revisión breve de avances en técnicas de análisis de estruturas y una discusión sobre dos casos de estudio, Monasterio de Jerónimos en Lisboa, Portugal, y Qutb Minar, en Nueva Delhi, India.

PALABRAS CLAVE: Comportamiento no-lineal; Análisis estructural; Ingeniería sísmica; Casos de estudio.

ABSTRACT:

Conservation and restoration of historical structures are still a challenge to modern practitioners even if considerable research advances have occurred in the last decades, namely with respect to non-destructive testing, mechanical characterization, tools for advanced numerical analysis, knowledge on traditional materials and techniques, and innovative materials and techniques. In the paper recent developments in structural analysis are briefly reviewed, and two emblematic case studies are discussed: Monastery of Jerónimos, in Lisbon, Portugal; Qutb Minar, in New Delhi, India.

KEY WORDS: Non-linear behavior; Structural analysis; Earthquake Engineering; Case studies.

1. INTRODUCCIÓN

The analysis of historical masonry constructions is a complex task that requires specific training. The continuous changes in materials and construction techniques, which swiftly moved away from traditional practice, and the challenging technical and scientific developments, which make new possibilities available for all the agents involved in the preservation of the architectural heritage, are key aspects in the division between the science of construction and the art of conservation and restoration.

The consideration of these aspects is complex and calls for qualified analysts that combine advanced knowledge in the area and engineering reasoning, as well as a careful, humble and, usually, time-consuming approach. Several methods and computational tools are available for the assessment of the mechanical behavior of historical constructions. The methods resort to different theories or approaches, resulting in: different levels of complexity (from simple graphical methods and hand calculations to complex mathematical formulations and large systems of non-linear equations), different availability for the practitioner (from readily available in any consulting engineer office to scarcely available in a few research oriented institutions and large consulting offices), different time requirements (from a few seconds of computer time to a few days of processing) and, of course, different costs.

The possibilities of structural analysis of historical constructions have been addressed e.g. in [1], where it is advocated that most techniques of analysis are adequate, possibly for different applications, if combined with proper engineering reasoning. Recent advances in terms of sophisticated analysis tools are discussed in [2]. It is noted that only very recently the scientific community began to show interest in modern advanced testing (under displacement control) and advanced tools of analysis for historical constructions. The lack of experience in this field was notorious in comparison with more advanced research fields like concrete, soil, rock or composite mechanics.

Modern intervention procedures require a thorough survey of the structure and an understanding of its history. Any heritage structure is the result of the original design and construction, any deliberate changes that have been made and the ravages of time and chance. An engineer working on historical buildings must be aware that much of the effort in understanding their present state requires an attempt to understand the historical process.

2. RECENT EXPERIMENTAL ASPECTS

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 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 [3,4]. Below, some recent advances are addressed.

2.1 COMPRESSIVE BEHAVIOR

The compressive strength of masonry in the direction normal to the bed joints has been traditionally regarded as the sole relevant structural material property. Nevertheless, the understanding about this behavior still requires more effort, both for short term and long term loading [5]. Figure 1a shows the simulation of a masonry representative volume under compression, with a continuum and particulate model. The differences found in terms of simulated compressive strength are up to 30%. Figure 1b shows a striking difference between strain rate values in short-term and long-term creep tests, meaning that the minimum duration of loading when conducting creep tests at high stress levels must be carefully selected.
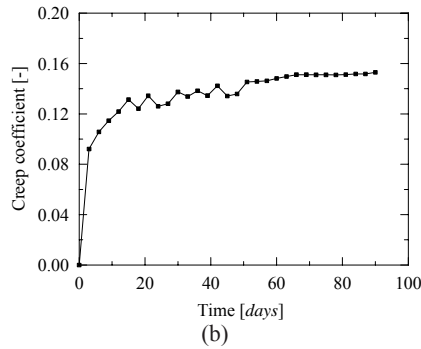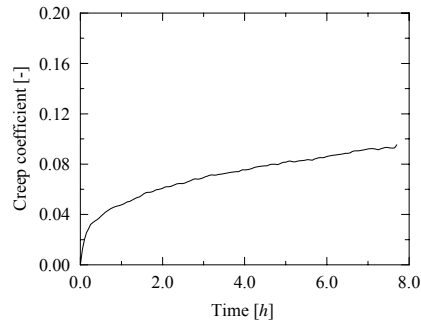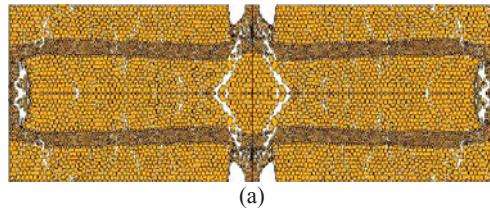
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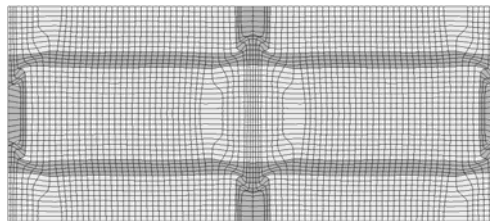
Figure 1. Masonry under compressive behavior: (a) short-term and (b) long-term loading.

2.2 STONE MASONRY SHEAR WALLS

Scarce experimental information is available for stone masonry walls and a comprehensive testing program was started at University of Minho, aiming at increasing the insight about the behavior of typical ancient masonry walls under cyclic loading [6]. 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 2. 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.


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(b)
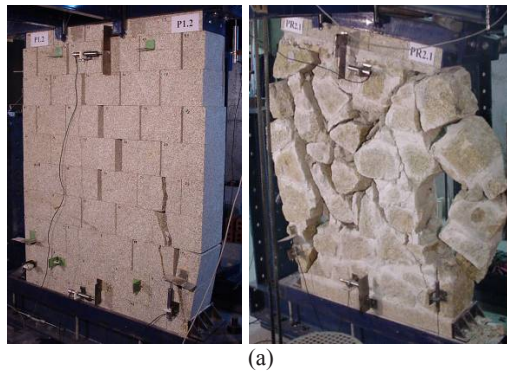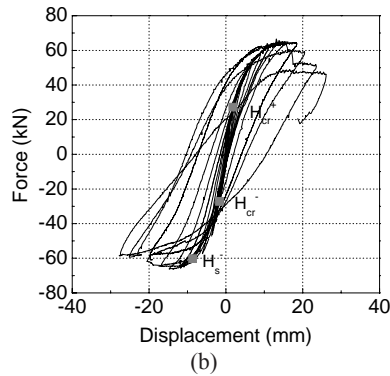
Figure 2. Behavior of stone masonry walls with different bond: (a) failure modes and (b) selected force-displacement diagram.

2.3 FRP REINFORCED MASONRY ARCHES

Among the materials used to repair or upgrade civil engineering structures, there has been an increasing interest devoted to the use of FRP (fiber-reinforced polymer) composites in the form of bonded surface reinforcements. A set of eight arches, built with traditional low strength materials, have been tested under a monotonic vertical load applied at the quarter span, with different positions for the strengthening. In addition, also the bond between masonry and FRP have been characterized in a testing program just completed [7], see Figure 3.

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(b)
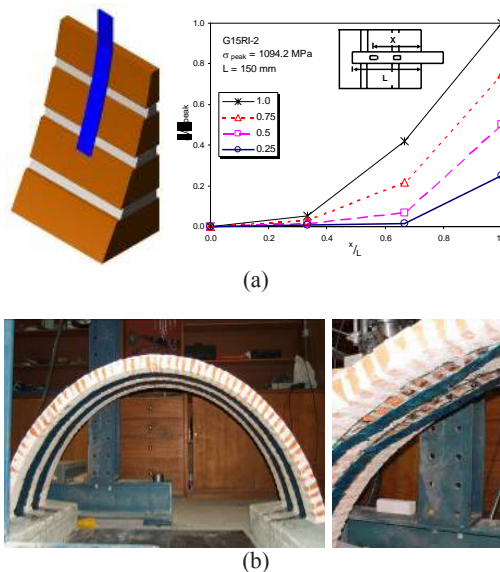
Figure 3. Traditional masonry strengthened with FRP: (a) bond tests with different masonry curvatures; (b) arch tests under point load.

3. RECENT DEVELOPMENTS IN NUMERICAL ANALYSIS

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 different modeling strategies 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 de-tails. 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 practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation.

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.

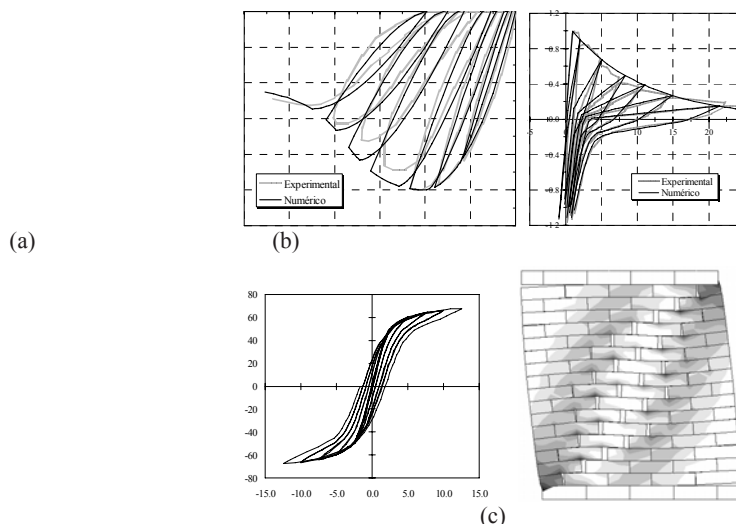## 3.1 DISCONTINUUM MODELS (MICRO-MODELING)

Different approaches are possible to represent heterogeneous media, namely, the discrete element method, the discontinuous finite element method and limit analysis.

The typical characteristics of discrete element methods are: (a) the consideration of rigid or deform-able blocks (in combination with FEM); (b) connection between vertices and sides / faces; (c) interpenetration is usually possible; (d) integration of the equations of motion for the blocks (explicit solution) using the real damping coefficient (dynamic solution) or artificially large (static solution). The main advantages are an adequate formulation for large displacements, including contact update, and an independent mesh for each block, in case of deformable blocks. The main disadvantages are the need of a large number of contact points required for accurate representation of interface stresses and a rather time consuming analysis, especially for 3D problems.

Discrete elements have been used for masonry e.g. in [8]. The finite element method remains the most used tool for numerical analysis in solid mechanics and an extension from standard continuum finite elements to represent discrete joints was developed in the early days of non-linear mechanics, with an early application to masonry [9]. On the contrary, limit analysis received far less attention from the technical and scientific community for masonry structures, even with also an early application in [10]. Still, limit analysis has the advantage of being a simple tool, while having the disadvantages that only collapse load and collapse mechanism can be obtained and loading history can hardly be included.

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.

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 [11]. By adopting appropriate evolution rules in a finite element environment [12], it is possible to reproduce non-linear behavior during unloading. Figure 4 shows the results of modeling a shear wall with an initial vertical pre-compression pressure. Figure 5 illustrates results using advanced solution procedures for non-linear optimization problems, with a limit analysis constitutive model that incorporates non-associated flow at the joints and a novel formulation for torsion [13].

(a) (b)

(c)

Figure 4. Behavior for an interface model extended to cyclic formulation: (a) tension-compression, (b) compression and (c) force-displacement diagram and collapse of shear walls.

3.2 CONTINUUM MODELS (MACRO-MODELING)

The finite element model seems to be the most adequate tool for the application of continuum models. Only a reduced number of authors tried to develop specific models for the analysis of masonry structures, always using the finite element method. A powerful plasticity model [14] 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 6 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.


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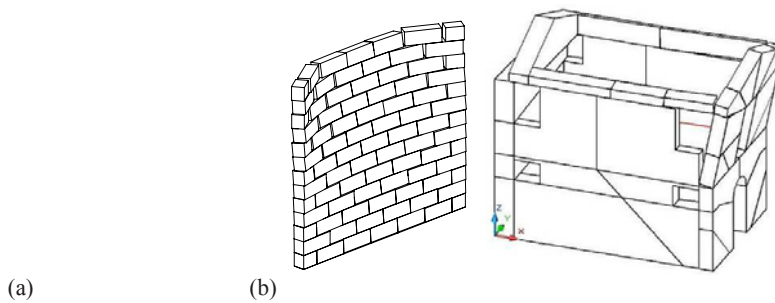
Figure 5. Results for rigid block limit analysis: (a) panel subjected to out-of-plane failure and (b) simplified analysis of a complete building with macro-blocks.

Another approach that is receiving much attention from researchers is the homogenization theory, in which the macro constitutive behavior of masonry is obtained from a mathematical process involving the geometry and the constitutive behavior of the masonry components. Figure 7 illustrates typical results obtained for homogenized failure surfaces and homogenized constitutive behavior [2].

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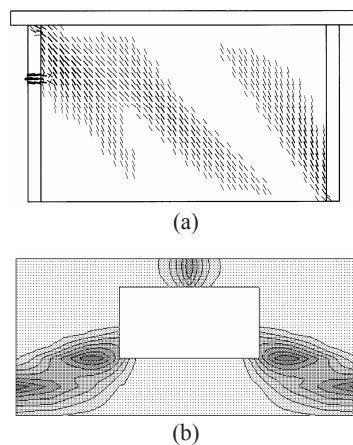
Figure 6. Results for macro-modeling analysis: (a) shear wall and (b) panel subjected to out-of-plane failure.

(a)

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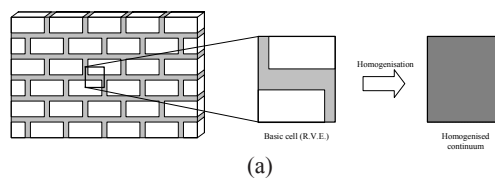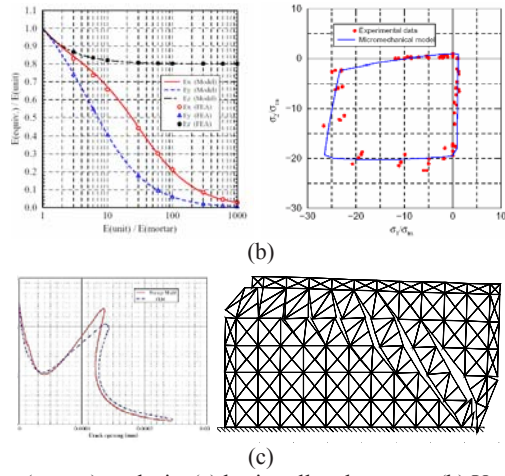
Figure 7. Results for homogenization (macro) analysis: (a) basic cell and process; (b) Young's modulus; (c) failure surface; (d) constitutive behavior in tension; (e) results of shear wall using limit analysis finite elements.

4. CASE STUDIES

4.1 MONASTERY OF JERÓNIMOS, LISBON

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). One court is composed by the Church and the cloister of the monastery. The plan church includes a single bell tower (South side), a single nave, a transept, the chancel and two lateral chapels.

The analysis of previous existing works allows concluding that the geometrical survey of the main nave demonstrates a vertical non-alignment for all the columns and the external walls Also, a radar investigation, ultrasonic / sonic tests carried out show that the columns of the nave seem to be of good quality and made of a single block or two blocks, and a variable thickness mortar layer seems to exist on the extrados of the vault. A concrete-like material with stones and clay mortar fills the fan capitals. Finally, an existing geotechnical report shows that the bed rock is located a few meters below the surface and direct foundations were used.

Considering that available data on structural parameters is quite scarce, it was decided to promote a campaign of experimental tests aiming at (a) mechanical characterization of the materials; (b) dynamic modal identification; (c) long term monitoring through the installation of static and dynamic monitoring systems.

Using the information gathered, several structural analyses have been made, making use of different models.

A first simplified model was used for the global structural analysis of the compound. The adopted mesh includes around 8000 elements, 23500 nodes and 135000 degrees of freedom. The time-effort necessary for total mesh generation, including definition of supports, loads and thicknesses, can be estimated in three man-months. Five independent non-linear analyses were carried out, namely for vertical loads and for seismic loading along two directions (with positive and negative sign). Figure 8a shows the deformed mesh at failure. The towers are the critical structural elements but the non-linear analyses using the simplified model seem to demonstrate that Monastery of Jerónimos is a reasonably safe construction in what concerns the wall behavior under seismic loading.

As the vaults have not been properly considered in the model, a conclusion regarding the safety of the vaults is not possible. For this purpose, a 3D model composed of beam elements (3 nodes, isoparametric formulation, axial and transversal integration) was adopted, see Figure 8b. The numerical results concerning the step-by-step seismic analysis for a 475 year return period scenario show that the monument is submitted to a significant stress state that causes cracking, but neither local nor global collapse is reached. However, the collapse of the South bell-tower by overturning is nearly to happen. More severe seismic scenarios are currently under analysis.

4.2 QUTB MINAR, NEW DELHI

Qutb Minar is the highest monument of India and one of the most important monuments of Delhi. The Minar rests on a 1.7 m deep ashlar masonry platform with sides of approximately 16.5 m, which in turn overlies a 7.6 m deep lime mortar rubble masonry layer, also square, with sides of approximately 18.6 m. The bedrock is located around 50-65 m below the ground level.

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(b)
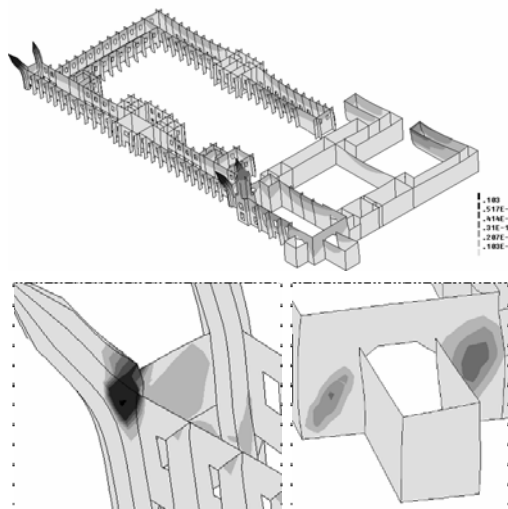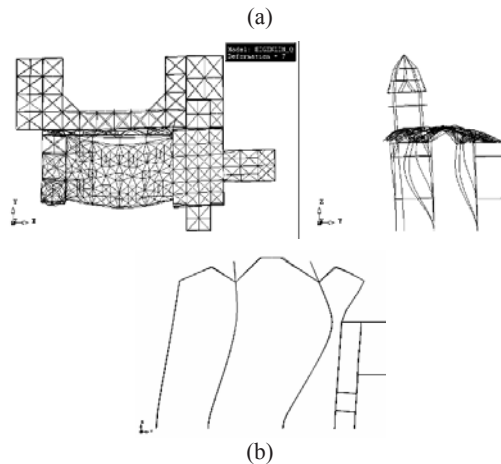
Figure 8. Selected results of the analysis of Monastery of Jerónimos: (a) pushover analysis: deformed mesh with contour of maximum displacements, and details with contour of crack width; (b) time integration: first mode shape and collapse mode.

The Minar cross-section is circular/polilobed, being the base diameter equal to 14.07 m and tapering off to a diameter of 3.13 m at the top, over a height of 72.45 m. The tower is composed by an external shell corresponding to a three leaf masonry wall and a cylindrical central core.

The materials have been identified and ambient vibration tests were performed with the aim to define the modal parameters (natural frequencies, mode shapes and damping coefficients). Fourteen natural frequencies and corresponding modes were defined.

For benchmarking, three different numerical models were considered to evaluate the structural behavior of the minaret. Two models use the well known Finite Element Method, both are three-dimensional models but one uses 3-D solid elements (Solid Model) while the other one was performed with 3-D composite beams (Beam Model). The third model uses 2D in-plane elements based on the Rigid Element Method (Rigid Model).

Model updating was performed in order to match the natural frequencies arising from the experimental investigation. Each model was updated independently and the elastic modulus was the parameter considered for the calibration of the different sets of materials, ranging between reasonable values for the different types of masonry.

Results are shown in Figure 9. It was possible to conclude that: (a) all models are capable of fitting rather well the measured frequencies and mode shapes; (b) all models provide a similar failure load under push-over analysis (proportional to the mass); (c) very large differences are found if a push-over analysis mass proportional, linear proportional or first mode proportional is adopted; (d) the failure mechanisms using push-over mass proportional analysis (at the base) and the failure mechanisms using time integration (at fourth balcony) are rather different; (e) updating the mass distribution proportional to the first mode during the push over analysis does not provide the actual failure mode at the top, observed in the past and the predicted using time integration.

5. 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 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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(c)

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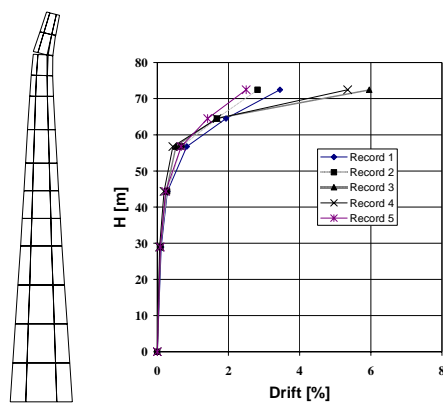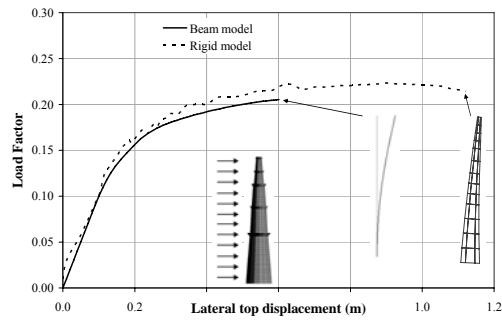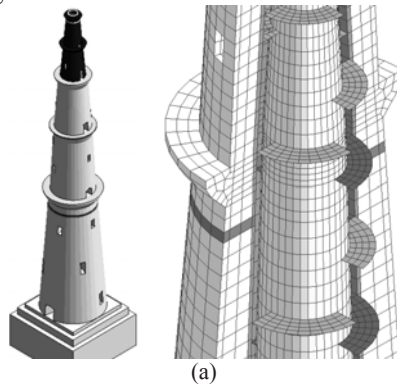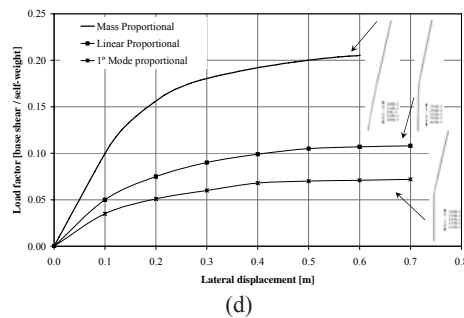
Figure 9. Selected results of the analysis of Qutb Minar: (a) 3D finite element mesh; (b) simplified models for time integration; (c) results of collapse mechanism for time integration using simplified models; (d) push-over analysis with beam element.

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7. RESUMÉ

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