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Seismic behavior and assessment of masonry heritage structures. Needs in engineering judgement and education

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Abstract

Built cultural heritage is at risk due to manmade and natural hazards. The seismic vulnerability of ancient masonry buildings is particularly difficult to assess and requires specialized technical skills. Key aspects are the materials properties and nonlinear effects, the morphology of the structural elements, the connections between structural elements, the stiffness of horizontal diaphragms and the building condition. This paper addresses the holistic approach recommended for the structural assessment of historic masonry buildings and the developments in the areas of inspection, diagnosis, monitoring and non-destructive testing, with applications to emblematic monuments. The methodology covers a step-by-step approach, based on historical research, an inductive study on similar structures, and a range of surveying, experimental, analytical and numerical tools, all aimed at evaluating the structural response and defining safety levels. Attention is given to the need of conservation engineering background of professionals and ways to attain this goal.

Keywords: Structural assessment; Limit analysis; Nonlinear pushover analysis; Nonlinear dynamic analysis; Damage survey and in-situ testing

1 Introduction to masonry heritage structures

Masonry is a heterogeneous material that consists of units and joints. The mechanical behavior of the different types of masonry has common features such as high specific mass, low tensile and shear strengths, and low ductility when loaded out-of-plane (quasi-brittle behavior). The behavior is known to be anisotropic and sensitive to the orientation of loads. Still, the incorporation of complex material laws in computer simulations and the use large models remains a challenge.

Historic masonry exhibits a vast dispersion of types, regarding units and joints, the presence of mortar and different bond arrangements. The geometrical characteristics of masonry elements (e.g. thickness, span or height), often with many discontinuities and alterations, provide additional uncertainties. In seismic areas, the overall response, corresponding damage and often, collapse, depends on the redistribution of seismic forces, amongst longitudinal and transversal walls, the level of connectivity in corner junctions and the presence of bracing elements. The latter, are mostly timber floors (and roofs) with flexible diaphragmatic action [1]. Indeed, the majority of historical buildings do not present stiff floors able to provide diaphragmatic action, the so-called integral or "box behavior" [2]. This type of structures exhibited poor performance in many past earthquakes. In general, they were designed for gravity loads (compressive behavior) not taking into account the high inertial lateral loads caused by earthquakes. Research conducted on flexible diaphragms showed that: (a) supports at floors behave as spring supports; (b) large deformation capacity and high strength of the floor are found with respect to its mass; (c) failure mechanisms of flexible diaphragms are related to the lack or weak connections between the masonry walls and diaphragms; (d) highly non-linear hysteretic behavior is found when peak ground acceleration is high; (e) strengthening of the horizontal diaphragms is a natural solution, even if an increase of the in-plane stiffness per se is usually not enough to improve the global response of the building. In addition, monumental structures present often large span to height ratios, with limited "horizontal" elements present (possibly arches, vaults or domes).

In this paper, the methods used for practice and research in Europe, in case of seismic assessment of heritage masonry structures, are briefly reviewed, namely limit analysis using macro-blocks, pushover analysis under different load patterns, and non-linear dynamic analysis with time integration. Finally, examples of emblematic monuments and engineering applications of these methods are shown.

The above concepts are specifically the objective of an education program in Europe (recipient of the most prestigious award for cultural heritage, Europa Nostra in

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2017): *Structural Analysis of Monuments and Historical Constructions* (www.msc-sahc.org), involving 375 students from 70 countries in the last 12 years. With the aim of disseminating knowledge in the study and repair of historical buildings, the International Journal of Architectural Heritage and the biennial *International Conference on Structural Analysis of Historical Constructions*, are also devoted on promoting this interdisciplinary approach. Lastly, the *Historical and Masonry Structures* (HMS) group (www.hms.civil.uminho.pt), active from 1996, at the University of Minho in Portugal, provides a wealth of advanced research in testing, modelling, assessment and strengthening of historical structures.

2 Structural safety assessment and masonry built heritage

The seismic assessment of masonry heritage structures is an integrated multi-disciplinary approach, based on a framework for the analysis, conservation and structural restoration defined in the ICOMOS/ISCARSAH recommendations from 2005 [3]. In general, the methodology of assessing a heritage building respects values of authenticity, structural and architectural integrity, and intangible building technologies. It involves a combination of research and diagnosis tools; i.e. historical research, inspection, monitoring and structural analysis. The main objective is to acquire a deep understanding and knowledge of the material characterization, the overall structural behavior, the level of connectivity between structural parts, and the subsequent changes and decay that occurred during the structure's lifespan.

The process of diagnosis, in a first level approach, is qualitative, mainly involving historical research and in-situ observations, to acquire information on the structural behavior and the existing damage. In order to know the causes of damage, the level of safety and the necessity of retrofitting, quantitative approaches need to be followed; mostly material characterization, in-situ and laboratory testing/monitoring, and structural analysis [3]. Given the uncertainty related to data, quantitative results are to be combined with empirical evidence; e.g. historical research, inspection and comparison with similar buildings, which bring in the relevance of personal experience and judgment to provide the best possible verdict.

After determining the causes of structural damage and decay, remedial measures might need to be taken, under a carefully established design process. Mostly through modelling and calculations, and the embodied hypotheses, the response is quantified, subjected to different actions and compared with threshold values from international standards and practices. Conservation and retrofitting measures, in addition to many other relevant criteria such as compatibility, cost or durability, enforce the concept of minimum intervention and efficiency, considering the likely benefit and harm. Only what is really necessary is to be implemented, having also the minimum impact on the historic fabric. Choices between traditional and innovative-modern retrofitting systems, with the corresponding use of materials, are always case related and balanced between the needs of safety, durability and protection of heritage values. Imminent safeguarding measures might be necessary to provide safety from collapse and total building loss. Even in those cases, actions should be undertaken so that measures can be reversible. Thus, permanent alterations of the historic fabric should be avoided. Sometimes, simple measures that address long-term performance, maintenance and durability can have more desirable effects, than massive and immediate retrofitting (Fig. 1) [3].

One must also bear in mind that the process of safety assessment and design of strengthening in historic masonry structures should not be necessarily based on the approach adopted for existing structures. Nominal, unreduced values of strength properties can be applied [4], together with lower values of actions for extreme events, such as earthquakes.

In general, the process of concluding on safety and remedial measures, presented schematically in Fig. 2, should respect the following steps: (a) acknowledgement of the general criteria to be adopted for the study of the cultural heritage buildings; (b) acquisition of data; (c) definition of the structural system and its behavior; (d) diagnosis and safety evaluation; (e) decisions on remedial measures [5].

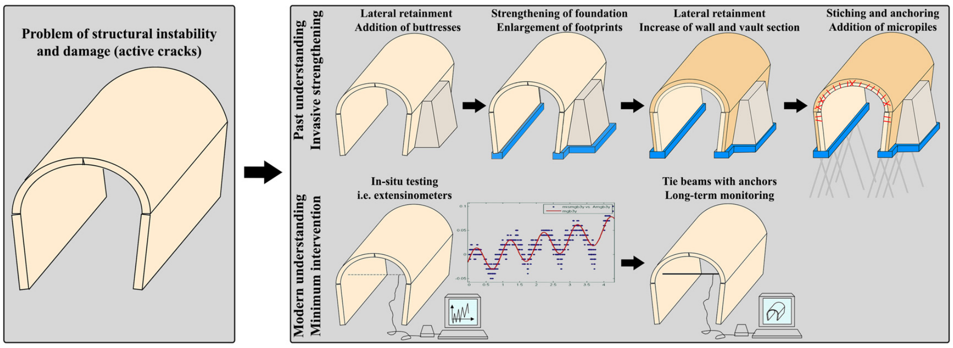

Figure1. Conservation and intervention. Blind confidence in modern and invasive techniques, with loss in authenticity and mistrust on the original capacity of the ancient structure vs. the modern understanding, combining minimum interventions and long-term monitoring.

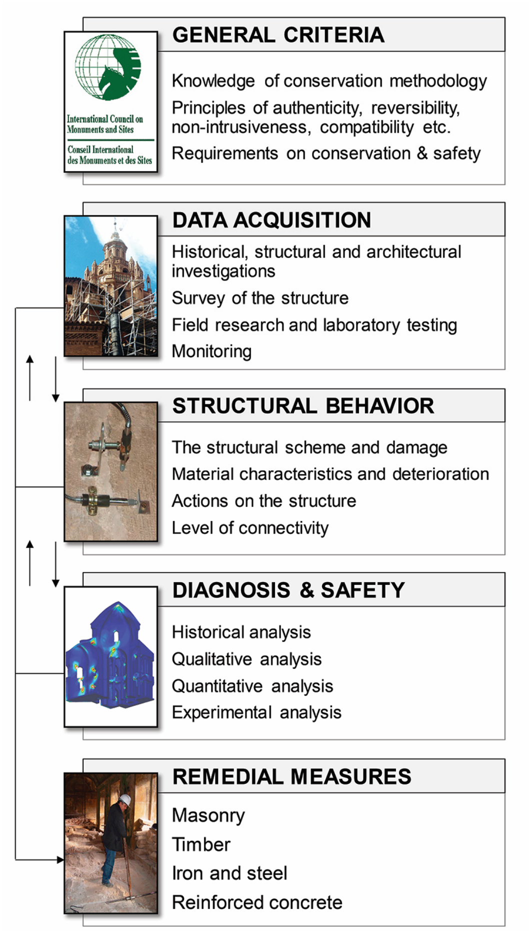

Figure 2. The ICOMOS methodology, adapted from [5].

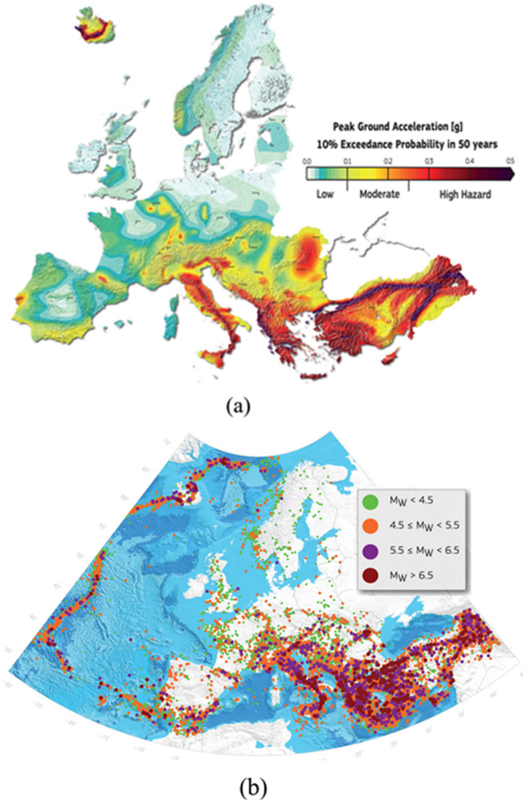

Figure 3. Seismic activity in Europe: (a) European seismic hazard map of 2013; (b) historical earthquake database for the period of 1000 to 2007 AD, with a magnitude range 1.7≤Mw≤8.5 for Europe, Central and Eastern Turkey, as compiled in the SHARE European Earthquake Catalogue (SHEEC) [4].

3 Seismic hazard mitigation under the historic perspective

The concept of seismic hazard is complex and results in immense socio-economic impacts worldwide. Peak ground acceleration (PGA) spatial distribution maps, with a 10% probability of exceedance within the next 50 years and a corresponding return period of 475 years [6], show that Europe and especially its southeast part, is characterized by moderate and high seismic hazard, and a long sequence of documented earthquakes (Fig. 3). Some hazard estimates even reach locally up to 0.75g, where g is the gravitational acceleration. As shown in Fig. 3, documented ground motions have exceeded values of 0.5 g [6]. The 1755 Lisbon earthquake had a range of magnitude of 8.5-9.0, with estimated base acceleration peaks of 0.3 g, in the center of a dense populated urban complex and is considered a 'supernatural' event. Triggering a tsunami of 10 m, leaving the city burning for 5 days, it destroyed 85% of the building stock, with casualties reaching 30% of the city's population (Fig. 4a) [7, 8]. Historically, this event is considered the starting point in Europe for the perception of the need for seismic hazard mitigation. As a consequence, seismic engineering solutions responding to this objective, using masonry buildings, were developed, with hybrid resistant systems of braced timber frames and masonry infills, known as "Pombalino" structures (Fig. 4b).

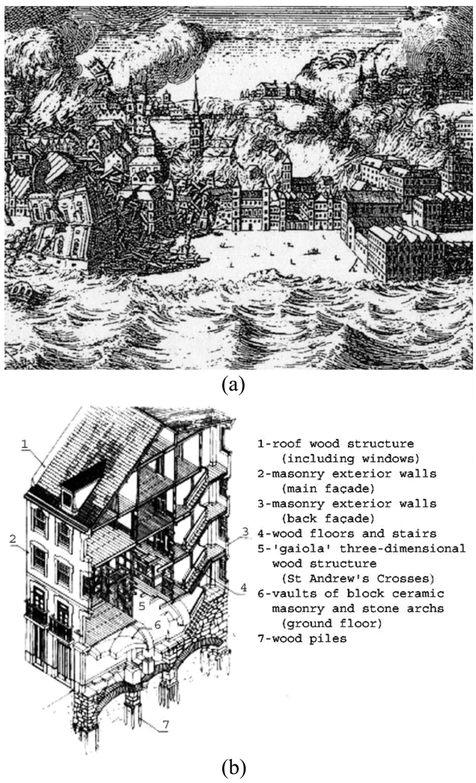

Figure 4. Lisbon earthquake 1755: (a) representation of the tsunami and fire, after the earthquake, from a German engraving [5]; (b) perspective drawing of a typical 'Pombalino' building, post to the earthquake [6].

4 Structural analysis

A structural model is a simplified representation of the reality, taking into account aspects of efficiency and computational restrictions. Still, any modelling strategy needs to provide geometrical and morphological consistency with the real structure. Aspects such as the type of connections, the interaction with soil and adjacent buildings, and the internal composition need to be described. The use of secondary structural elements, structural separations in buildings or local models should be used wisely and only in confidence that they represent the overall or localized structural behavior [9, 10].

The main objective of structural analysis for existing structures is to evaluate the structure's safety levels under the ultimate limit state (ULS); i.e. the capacity of sustaining gravity loading, the lateral capacity under seismic loading and other actions. A comparative vulnerability evaluation is often helpful, with alternative analytical and numerical tools, between global and local models, in order to increase confidence on the results. The most popular types of structural analysis tools are: (a) finite element (FE) strategies, under a macro- or micro-modelling, and discrete element methods (DEM); (b) limit or macro-block analysis, under a kinematic or a static approach. The concept of non-linearity, geometrical and/or physical, including the ability of the structure to dissipate energy and accumulate damage, can be incorporated in the methods, which increases the accuracy of the acquired response [10, 11].

Linear elastic analysis can serve as a preliminary tool, giving preliminary information about deformability and stress distribution. Yet, it provides often unrealistic responses for unreinforced masonry structures, with incorrect (and over-conservative) values of capacity and structural safety. Due to the very low tensile capacity in masonry structures, the response is highly non-linear, even under moderate stress states. Using linear elastic analysis, load paths are assumed constant and the overall structural behaviour and damage, under any action, cannot be predicted up to collapse level, e.g. [12, 13].

4.1 Modeling and analysis methods

Two basic types of computational representations of masonry material coexist; i.e. macro-modelling and micro-modelling. Macro-modelling is the most popular approach for large-scale models and is based on *Continuum Mechanics*; in other words, a homogeneous modelling approach, where masonry is modelled as a fictitious homogenized isotropic or anisotropic material. Plasticity, cracking and/or damage constitutive laws for tensile, shear and compressive softening behavior are assigned; e.g. the total rotating strain crack model, incorporating fracture energy values [11]. Discontinuities and cracks can be assigned to interface elements or a series of springs. Macro-modelling, combined with in-situ testing and historic research has been used for analyzing the structural behavior and lateral safety of various masonry emblematic structures, such as the Imperfect Chapels of Batalha Monastery, in Portugal (Fig. 5), the Cathedral of Canterbury, in UK (Fig. 6) and the Cathedral of Ica, in Peru (Fig. 7) [12, 13, 14].

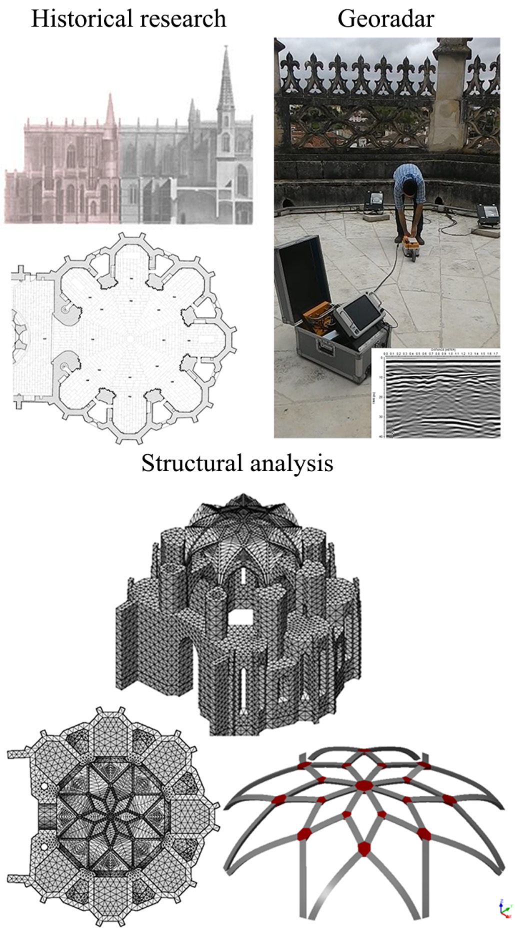

Figure 5. Conservation of cultural heritage buildings, methodology and application to case studies: Imperfect Chapels of Batalha Monastery in Portugal [12].

In the micro-modelling approach, masonry is represented as a composite, with the units and mortar modelled as continuous elements, whereas the discontinuity between them is explicitly modelled. Applications can be carried out with finite elements, discrete elements (DEM) and limit analysis. Usually, only the units and the mortar-unit interface (i.e. the joints) are modelled. Material behavior is often incorporated through a combined cracking-shearing-crushing material model, for the interface elements, while the units are often modelled as linear elastic [15]. Micro-modelling is a common practice in small scale models, but due to the advance in computational capabilities, it can be used also in large scale models. DEM, besides aspects of nonlinearity, allows the complete separation of blocks and the evolution of large displacements, which are also excellent for educational purposes; e.g. the Church of Kuño Tambo, in Peru (Fig. 8) and the Roman Temple of Évora, in Portugal (Fig. 9) [16, 17].

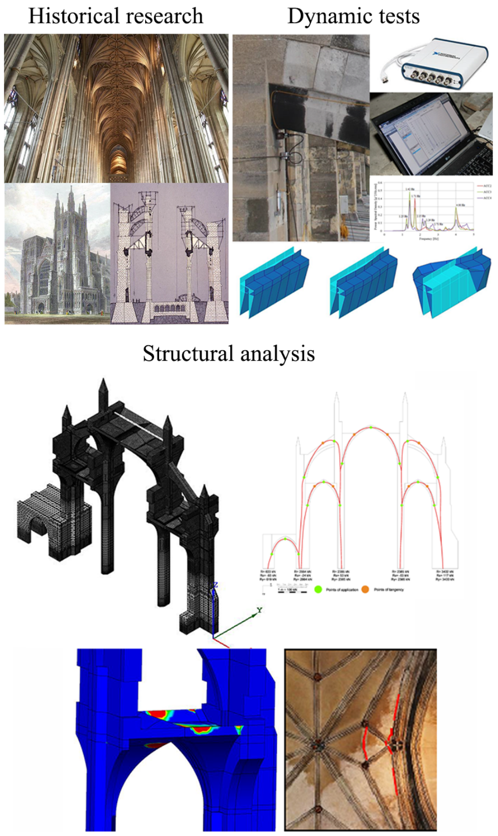

Figure 6. Conservation of cultural heritage buildings, methodology and application to case studies: Cathedral of Canterbury in the UK [13].

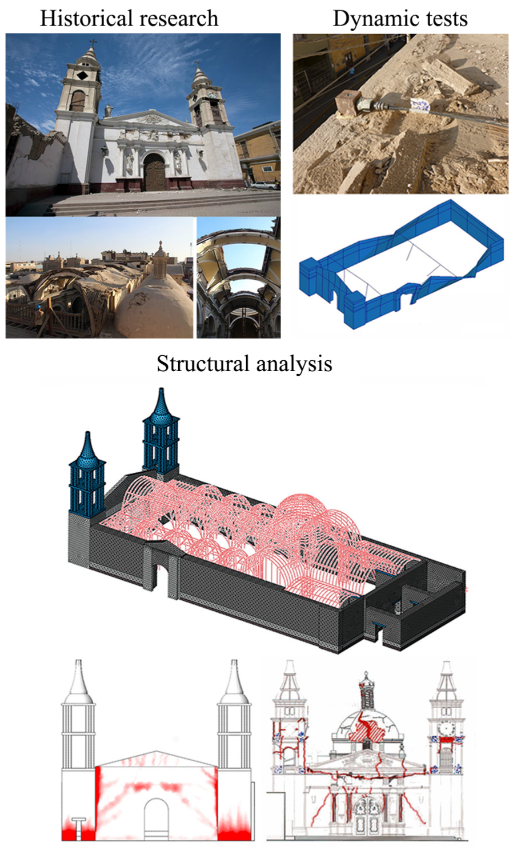

Figure 7. Conservation of cultural heritage buildings, methodology and application to case studies: Cathedral of Ica in Peru [14].

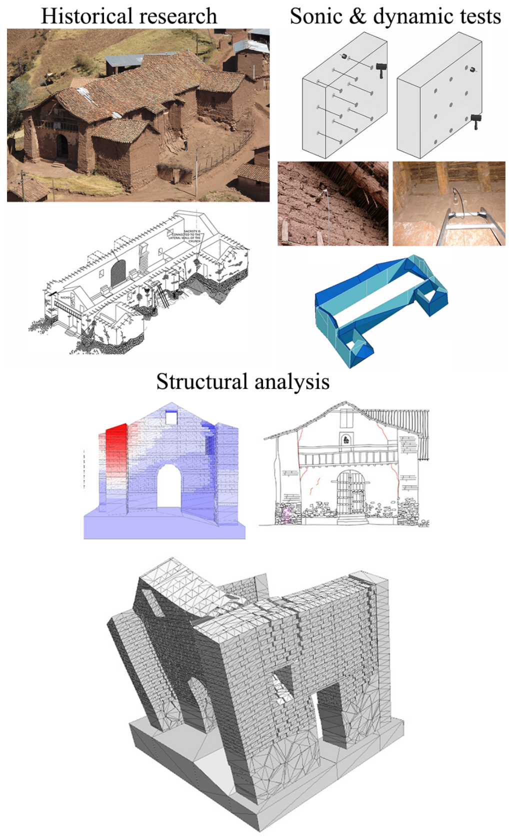

Figure 8. Conservation of cultural heritage buildings, methodology and application to case studies: Church of Kuño Tambo in Peru [16].

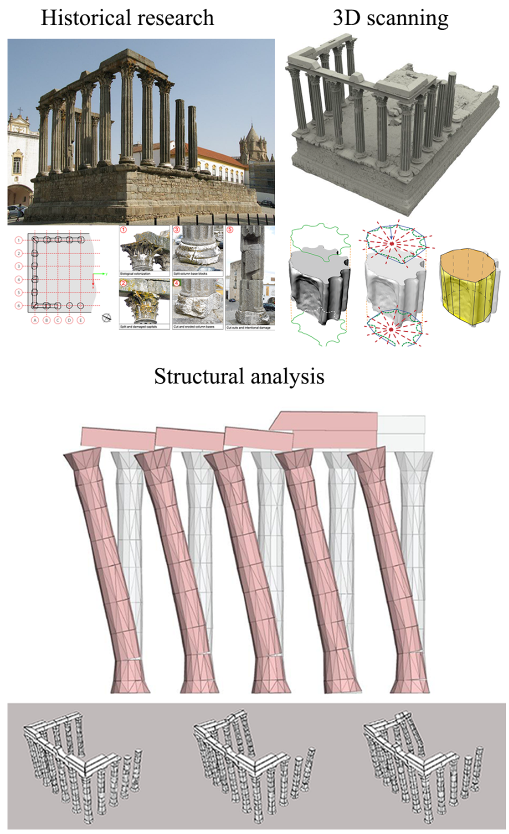

Figure 9. Conservation of cultural heritage buildings, methodology and application to case studies: Roman Temple of Évora in Portugal [17].

4.1.1 Pushover analysis

Regarding seismic effects, an equivalent static approach with lateral loading is often applied using a specific load pattern distribution, in all primary directions, until the structure enters post-peak behavior and collapses. Maximum capacity values and safety levels, in each direction, are obtained. Failure mechanisms are assessed mainly from maximum compressive stresses and cracks. Pushover analysis is considered the most appropriate seismic safety assessment technique for the assessment of masonry heritage structures, in terms of computing time and capacity to replicate the structural performance. Here, lateral load patterns can be mass proportional, using an inverted triangle and 1st mode proportional. Yet, given the lack of floor diaphragmatic stiffness and the out-of-plane failure, the collapse of many masonry heritage structures matches that of a rigid body. Thus, the mass proportional lateral load pattern is often considered more appropriate. Unlike most modern buildings, masonry heritage structures usually present many local modes, with low mass participation values. Thus, pushover analysis with load patterns proportional to a dominant mode tend to give unrealistic responses.

4.1.2 Nonlinear dynamic analysis

Nonlinear dynamic analysis with time integration, material nonlinearity and viscous damping, is the most accurate approach, to simulate a global structural response under seismic loads. Yet, for large numerical models, it is a complex and time consuming analysis that requires vast computational capabilities. In addition, it is not easy to define collapse. Under the recommendations of e.g. the European normative, at least seven time-history analyses are needed, for mean output values to be considered [18]. For a lower number of analysis, one can consider the maximum outputs. Base excitation is applied through uncorrelated sets of artificial or natural accelerograms, even if the former are required for a code based safety assessment.

In masonry heritage buildings, the tensile damage is distributed, with cracks closing, reopening and propagating [19]. Damage patterns can be obtained through cumulative damage plots, under scanning of maximum principal strains for the duration of the dynamic event [9]. One should keep in mind that single results are qualitative, given the randomness of the seismic event, but in general, they present good correlation with in situ documented damage patterns.

4.2 Analytical methods. From kinematic to rocking mechanisms

Ancient masonry structures were designed with geometrical rules for arches and buttresses. Since the 18th century, the concept of a limit analysis, also known as 'graphic statics' or 'thrust line', was adopted for the stability of arches and buttresses, with a finite number of force trajectories, contained within their boundaries (Fig. 10a & b). For the assessment of failure, under lateral forces, using kinematic analysis, an abacus of possible out-of-plane collapse modes is available, calculated mostly under relative rotations between parts (Fig. 10c & d). Masonry blocks are assumed as having zero tensile strength and enough friction to prevent sliding [20].

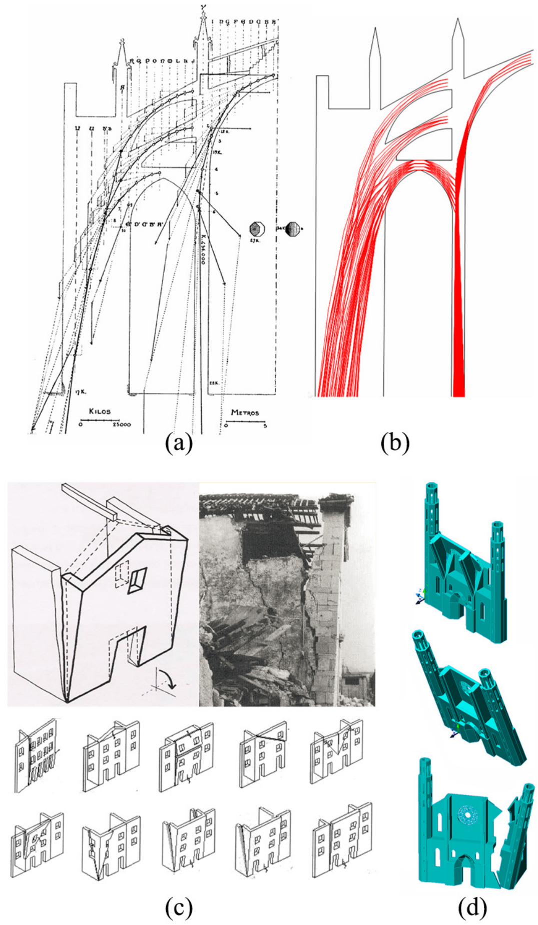

Figure 10. Mallorca cathedral: (a) Thrust line application from Rubió, 1912; (b) numerous alternative thrust lines, from analytical calculations [24]. Kinematic analyses: (c) an abacus of out-of-plane overturning modes [25]; (d) definition of collapse mechanisms for the façade of Santa Maria del Mar church in Barcelona [10].

In the modern assessment perspective of masonry heritage buildings, limit analysis, is now enhanced with local performance seismic criteria, such as ductility and displacement control demands, from design response spectrums. The approach is included in the Italian standards for the seismic evaluation of buildings and is a popular trend in engineering practice in Europe [21, 22]. Under careful considerations and in terms of lateral capacity values, limit analysis can correlate well, even with complex numerical modelling [9]. Here, engineering judgement and in-situ inspections are essential to improve confidence levels on potential failure mechanisms.

As an advanced technique, the monolithic out-of-plane response to earthquakes, of masonry structural parts, is explained by means of rocking dynamics. The process requires complex analytical or numerical calculations of an incremental kinematic analysis, under an acceleration-time history [23].

5 Conclusions - Recommendations

The seismic assessment of masonry heritage structures, aims at reproducing existing damage patterns and obtaining safety levels under current conditions. Yet, the whole process is demanding, in terms of conservation engineering skills and depends on the choice of modelling strategies, level of material characterization and in-situ testing. Combinations of simplified and advanced structural analyses tools, validated through in-situ inspections and monitoring, will provide the best validation of the structural response, safety and remedial measures. In cases where limited knowledge is available, the structural engineer in charge needs to have sufficient experience not to compromise the level of accuracy of the acquired results.

The uncertainty and limited applicability of current codes for the assessment of masonry heritage buildings emphasizes on the vital role of advanced education and dissemination of engineering practices in the field. Europe has been rather active, not only in developing advanced experimental and numerical techniques, but also in creating the adequate engineering environment, including: (a) specialized education programmes in the field of heritage structures; (b) specialized technical and scientific journals that covers technical issues on analysis, conservation and restoration of monuments and heritage buildings; (c) specialized series of conferences. Therefore, there is ample information available for professionals.

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