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Seismic vulnerability assessment of historical masonry structural systems

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ABSTRACT

Masonry structures are complex systems that require a thorough and detailed knowledge and information regarding their behavior under seismic loading. Appropriate modeling of a masonry structure is a prerequisite for a reliable earthquake resistant design or assessment. However, modeling a real structure to a robust quantitative (mathematical) representation is a very difficult, complex and computationally demanding task. This paper presents a methodology for earthquake resistant design or assessment of masonry structural systems. The entire process is illustrated using case studies from historical masonry structures in the European area. In particular, the applicability of the proposed method is checked via analyses of existing masonry buildings in three countries, namely Greece, Portugal and Cyprus, with different seismicity levels, influencing the risk impacting the masonry structures. Useful conclusions are drawn regarding the effectiveness of the intervention techniques used for the reduction of the vulnerability of the case-study structures, through the comparison of the results obtained.

1. Introduction

The majority of the main structural systems for historical structures are masonry elements, composed of stone, bricks, adobe and mortar. For many old historical masonry structures (including monuments) erected in zones of moderate to high seismicity, earthquake is one of their principal threats due to their limited earthquake resistance capacity [1], let alone other problems associated to the misuse or lack of proper maintenance. A successful intervention on a monument requires a good comprehension of its structural behavior under static and dynamic (earthquake) loading. An Engineer, taking part in the restoration process of a historical structure, through the analysis of its structural system, has to face the demanding task of checking and providing the structure with adequate capacity to withstand future actions with certain limits of damage, while bearing in mind the characteristics and values which make the structure unique and worthy of special attention. This has to be carried out within the conditions imposed by past or current regulations and scientific Charters (e.g. the Athens Charter 1931 [2], the Venice Charter 1964 [3], etc.), which make the whole process of analysis more demanding.

Masonry constructions are typically complex structures and there is lack of knowledge and information concerning the behavior of their structural systems, particularly in what regards their seismic response. Typically, these structures are more massive than today's structures and usually carry their actions primarily in compression.

Successful modeling of a masonry historical structure is a prerequisite for a reliable earthquake resistant design or assessment. For modern structures, with new industrial materials (reinforced concrete, steel, etc.), the development of a reliable mathematical model is possible, due to the fact that materials and member characteristics are more uniform and mostly explicitly known. On the other hand, for the case of masonry, and especially for the traditional plain one, it seems that there is a lot to be done in this field, until Engineers become more confident about the accuracy of the modeling.

For the purpose of masonry analysis and design, an operationally simple strength criterion is essential, taking into account the many uncertainties of the problem. Systematic experimental and analytical investigations on the response of masonry and its failure modes have been conducted in the last decades. Numerous analytical criteria have been proposed for masonry structures [4–6]. The main disadvantage of many existing criteria is that they ignore the distinct anisotropic nature of masonry, not to mention problems

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arising from differences within its thickness, and models not ignoring that behavior consist of more than one type of failure surfaces leading to an additional effort in the analysis process of the masonry structures [7]. According to Zienkiewicz et al. [8], the computation of singular points on failure surfaces may be avoided by a suitable choice of a continuous surface, which usually can represent, with a good degree of accuracy, the real condition.

Since reliable experimental data in the combined-stress state are rising rapidly [9–11], it is, therefore, the right time to examine the validity and utility of existing criteria, and to propose a failure surface of convex shape suitable for the anisotropic nature of masonry material. According to Hill [12] and Prager [13], the failure surface for a stable material must be convex. This, in mathematical terms, is valid if the total Gaussian curvature K of the failure surface is positive.

As can be concluded, various researchers have been working on the earthquake resistant design of masonry structural systems and especially on determining a strength criterion, but there is still a lot ongoing research on this field. In addition, aspects regarding the in- and out-of-plane behavior of 2- or 3-leaf masonry are not yet covered in detail. In the present study, masonry is considered as a single leaf one and is modeled as a homogeneous elastic material.

In this paper the framework of thought for such interventions is first discussed and then the steps of the proposed methodology are outlined. Following these, mathematical modeling issues, including failure criteria, are presented. Possible intervention techniques are described and then the results of the application of the proposed methodology in three case-studies are presented, followed by a comparison of the results and conclusions.

2. General methodology

Structures of architectural heritage present a number of challenges in conservation, diagnosis, analysis, monitoring, repair and strengthening that limit the application of modern codes and building standards. Recommendations are desirable and necessary to both ensure rational methods of analysis and intervention methods appropriate to the cultural context [14].

2.1. Framework of thought

Our research has adopted the rationale resulted from the work developed within the ICOMOS 2001 [15] scientific committee ISCARSAH (International Scientific Committee of the Analysis and Restoration of Structures of Architectural Heritage) and, in particular, by the *ICOMOS Charter: Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage* (ISCARSAH *Principles*). This framework of thought is delineated by the principles of: research and documentation, authenticity and integrity, compatibility (both visual and physical and/or chemical), minimal intervention and the degree of reversibility, as it is very seldom possible to achieve a fully reversible technique. They are in harmony with those that are the foundation of the *Athens* and *Venice Charters* and *The Secretary of the Interior's Standards for Historic Preservation Projects* [16].

2.2. ICOMOS recommendations

Differing opinions has been a characteristic of the field throughout its long history in its attempts to establish criteria for rehabilitation of historic and monumental structures. Nevertheless, a widely accepted framework is the Venice Charter [3], which was formulated in May of 1964, as a result of deliberations of many specialists and technicians in the restoration of historic monumental structures. During that congress, among many issues discussed for the preservation of historic structures, the Charter focused on achieving harmony between the existing structure and the new rehabilitation work performed upon it. According to the Charter, such interventions must follow the following basic principles: material compatibility, conservation of overall lay-out or decoration and mass–color relationship, avoidance of the removal of any part, or additions to the building. The Charter requires detailed documentation of all rehabilitation works by means of critical reports (including drawings and photographs) and recommends its publication. According to ICOMOS recommendations, a thorough understanding of the structural behavior and material characteristics is essential for any project related to the architectural heritage. It is recommended that the work of analysis and evaluation should be done with the cooperation of specialists from different disciplines, such as earthquake specialists, architects, engineers and art historians. In addition, it is considered necessary for these specialists to have common knowledge on the subject of conserving and upgrading or strengthening the historical buildings.

The methodology puts emphasis on the importance of an "Explanatory Report", in which all the acquired information, the diagnosis, including the safety evaluation, and any decision to intervene should be fully detailed and justified. This is essential for future analysis of continuous processes affecting the structure (such as decay processes or slow soil settlements or other side-effects), or phenomena of cyclical nature (such as the variation in temperature or moisture content) and even phenomena that can suddenly occur (such as earthquakes or hurricanes), as well as for future evaluation and understanding of the remedial measures adopted at present.

2.3. Proposed methodology

Based on ICOMOS principles and recommendations, as well as on other similar works [17–27,1,28,29], a restoration methodology for historical masonry structures has been developed and presented here as a contribution to the solution of this complex problem. A flowchart of the proposed methodology is illustrated in Fig. 1. In the framework of the proposed methodology, the following eight distinct steps are included:

2.3.1. Step 1: Historical and experimental documentation

There are some aspects that should be followed before carrying out a rigorous structural analysis, which are listed below [29].

(a) Experience shows that the structural analysis regarding the seismic response of a Monument is an integral part of the broader study of the Monument; history and architecture of the Monument are indispensable prerequisites for the structural analysis, in order to account for all initial and consecutive construction phases, previous interventions or additions, etc.
(b) Description of existing damages and/or previous interventions (visible or possibly hidden ones), together with their in-time evolution; monitoring may be helpful.
(c) Systematic description of the materials, including their interconnections. Connections of perpendicular walls or of walls and floors should be thoroughly investigated.
(d) Results of experimental investigations regarding: geometrical data, *in situ* evaluation of the strength of materials, structural properties of masonry walls, dynamic response of the construction, subterranean data, as well as results of possible previous monitoring (displacements, settlements, internal forces, humidity, groundwater level, cracks' opening, seismic accelerations, environmental data, etc.).
(e) Description of the structural system, in a systematic and detailed way.