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Failure analysis of Monastery of Jerónimos, Lisbon: How to learn from sophisticated numerical models

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Abstract

Conservation and restoration of historical structures are still a challenge to modem practitioners even if significant research advances have occurred in the last decades. Significant advances have been made in non-destructive testing, mechanical characterization, tools for advanced numerical analysis, knowledge on traditional materials and techniques, and innovative materials and techniques. In the paper, Monastery of Jerónimos in Lisbon, Portugal is adopted as a case study for structural safety assessment. A first discussion is held on the difficulties related to the need of adopting simplified geometries of the model. After a set of sophisticated non-linear failure analyses, a second discussion is held with respect to the consequences associated with the results obtained. Finally, additional in situ testing and monitoring are carried out in a truly iterative process of knowledge accumulation before defining any remedial measures.

Keywords: Structural failures; Finite element analysis; Damage assessment; Non-destructive inspection; Failure analysis

1. Introduction

Time shows that many historical masonry constructions collapsed due to accidental actions such as earthquakes, but not only exceptional events affect historical constructions. Fatigue and strength degradation, accumulated damage due to traffic, wind and temperature loads, soil settlements and the lack of structural understanding of the original constructors are high risk factors for the architectural heritage. Therefore, structural analysis and safety assessment of historical masonry buildings are often necessary.

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''. Still, the mechanical behavior of the different types of masonry has generally a common feature: a very low tensile strength. This property is so important that it has determined the shape of ancient constructions. Nevertheless,

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the difficulties in performing advanced testing of ancient structures are quite large due to the innumerable variations of masonry, the variability of the masonry itself in a specific structure and the impossibility of reproducing it all in a specimen.

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. It should be expected that results of different approaches are also different, but this is not a sufficient reason to prefer one method from the other. In fact, a more complex analysis tool does not necessarily provide better results. Most techniques of analysis are adequate, possibly for different applications, if combined with proper engineering reasoning. Nevertheless, accurate modeling requires a thorough experimental description of the material. The reader is referred to [1–3] for a more comprehensive discussion on these issues. A basic notion is softening, which is a gradual decrease of mechanical resistance under a continuous increase of deformation forced upon a material specimen or structure. It is a salient feature of soil, brick, mortar, ceramics, rock or concrete, which fail due to a process of progressive internal crack growth.

Recently, Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage have been approved by ICOMOS [4]. 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. The recommended methodology for completing a project is shown in Fig. 1, where an iterative process is clearly required, between the tasks of data acquisition, structural behavior, and diagnosis and safety. In particular, diagnosis and safety evaluation of the structure are two consecutive and related stages on the basis of which the effective need for and extent of treatment measures are determined. If these stages are performed incorrectly, the resulting decisions will be arbitrary: poor judgment may result in either conservative and therefore heavy-handed conservation measures or inadequate safety levels.

Here, Monastery of Jerónimos in Lisbon, is adopted as a case study of an attempt to use modern techniques and recommendations for the safety assessment of the compound. In particular, two different aspects are considered: (a) the safety of the full monastery compound under seismic loading, in which five different load

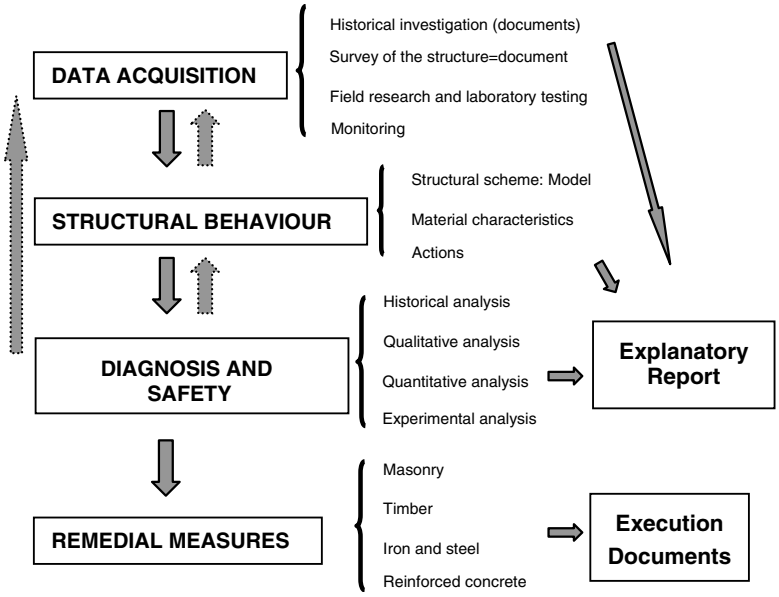

Fig. 1. Flowchart with the methodology for structural interventions proposed by ICOMOS [4].