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Collapse and upgrading mechanisms associated to the structural materials of a deteriorated masonry tower. Nonlinear assessment under different damage and loading levels

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ABSTRACT

This research focuses on a specific issue: the role of both structural and retrofitting traditional materials (mortar and bricks) on the collapse and structural upgrading mechanisms of a damaged square masonry structure under static and dynamic loading. The potential/limitation of traditional structural materials as retrofitting elements is analysed, as well as their implication in failure/improvement progression. The sensitivity of the structural response to different damage states is investigated using finite element models. A constitutive model is arranged on the basis of prior theories, in order to take into account the singularities of the dynamic response of deteriorated masonry structures, including interlocking, and cracking/crushing. Static, modal and transient analyses are computed in the nonlinear range. The degrading mechanisms and the damage origin are analysed and singled out, as well as the effect of the restoration materials on the safety response improvement. As a main result, it was found the possible origin of a foundation settlement and weak points which are prone to suffer damage were identified. The poor quality of the structural materials increases the fundamental period more than the inclusion of the complete crack pattern The transient simulations carried out showed that when traditional repair materials are applied, 60% increase for shear and 24% decrease for displacement are achieved, and the fundamental period is significantly decreased. Results allow optimizing future repair works, making the most of traditional materials.

1. Introduction

The analysis of the different failure mechanisms of damaged masonry structures is a complex task, being both the mechanical control parameters and their associated numerical models two crucial issues in order to obtain reliable results. The problem is increased if the structural performance under seismic loading is required. Under that premise, predicting the hierarchy of failure mechanisms is a crucial issue. Thus, elastic analyses are not adequate and the inelastic structural response is required. In addition, it is crucial to distinguish between stable damage patterns and damage evolution leading to a global collapse [1]. Moreover, as stated by Foraboschi [2], Codes exhibit an excessive conservatism as they do not consider the contribution of masonry tension strength and texture interlocking.

In the last decades, many researchers were involved in the development of numerical tools as an alternative to the rules-of-thumb or empirical formulae that have been traditionally applied when a masonry building is assessed [3]. Under this framework, nonlinear finite element method, FEM, is the most common advanced strategy to simulate the safety response of masonry structures. Numerical analysis improves the knowledge of the structural behaviour of masonry structures and can play a role in the

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process of structural recovery and reinforcement of age-old constructions [4]. If a structure is going to be analysed in the nonlinear range via FEM, a main concern is the definition and the use of suitable material models. If accurate results are pursued, this is a crucial step owing to the heterogeneity and the uncertainties associated to the masonry material. Moreover, it is worth to note that it is difficult to predict the response of damage and brittle masonry structures since their response is extremely nonlinear. The most of the structural input parameters are uncertain, and the question of which sources of uncertainty most strongly affect possible repair measures is an ongoing research. Prior researches focused on the effects of uncertainties on the seismic response parameters of masonry structures (e.g. [5]). Different methodologies for the simultaneous incorporation of the uncertainties for seismic performance assessment have been proposed, being usually computationally demanding [6]. However, the sensitivity associated to traditional structural materials and retrofitting materials and their control parameters, in heritage structures is an open question. As far as the collapse mechanisms is concerned, Lourenço states that regardless of the type of modelling adopted the following failure mechanisms, characteristic of masonry, must be considered [7]: (a) Cracking in the joints; (b) Sliding along bed or head joints at low values of normal stress; (c) Cracking of the units in direct tension; (d) Diagonal tension cracking of the units at values of normal stress sufficient to develop friction in joints; (e) Splitting of the units in tension as a result of mortar dilatancy at high values of normal stress. Foraboschi points out that the failure mode of a masonry structure is dictated by the weakest kinematic mechanism and that crushing is not a significant mode of failure for masonry structures, excluding elements made of poor masonry or subjected to moisture and salt crystallization [8,9]. Thus, if a deteriorated masonry structure is going to be assessed failure can be dictated by crushing. In addition, recent researches focus on the fact that masonry crushing is the result of crack propagation, being a mode of failure similar to concrete crushing [10].

Previous works have provided new strengthening methods for masonry structures (e.g. those of proposed by Foraboschi and Vanin [11]) However, when heritage structures are analysed to improve the structural response, it is no usual to analyse the intrinsic retrofitting potential of traditional materials. Besides, it is no common to analyse the influence of those materials in the damage evolution from the hypothetical original state. This research focuses on a specific issue: the role of both structural and retrofitting traditional materials (mortar and bricks) on the collapse and upgrading mechanisms of an ancient masonry structure under static and dynamic loading.

From the aforementioned, a numerical assessment of an al-Andalus period construction, the Salares tower, is provided. The study takes into account the state of decay of its building materials and structural elements. This tower exhibits dramatic damage, such as large cracks and spalling, and no safe response is expected in its present state of conservation. Indeed, this construction is very prone to suffer a progressive damage propagation, which in the long-term could possibly lead to a global failure. Thus, a comprehensive structural study that may evaluate its actual constructive and structural features, to counteract the formation and propagation of damage is needed. Interlocking between materials is considered. The stress–strain matrix is adjusted in order to control the cracking phenomena under seismic loading and two shear transfer coefficients for open and closed cracks are applied The effect of traditional restoration materials on the structural response is also analysed, in order to optimize future repair works, making the most of traditional materials.

All those numerical approaches deliver an estimate of structural safety level, providing crucial information on the role of the structural materials on the collapse and upgrading mechanisms. The numerical analyses provide evidence of the real nature of the structural weakness, as well as allow identifying the origin of mechanical deterioration phenomena.

2. Constitutive model and control parameters

In this Section, the following issues are shown: the specific characteristics of the applied constitutive model (a model established by prior theories and cracking/crushing capable), the singularities of the dynamic response of deteriorated masonry structures and the values of the control parameters that are required.

2.1. Geometric, constructive and damage description of the structure

The Salares tower is a medieval structure of medium size, 3.30×3.30 m^2 on lower plan, and it rises 17 m above the current ground level. Morphologically, it is divisible into three structural parts, namely external walls, central core and barrel vaults. Average thickness of walls is 0.55 m, core cross-section is 0.90×0.90 m^2 and barrel vaults section is 0.15 m. The inner chamber consists of an anti-clockwise staircase covered by horizontal barrel vaults, which ascend around the central solid core. The outside walls are perforated by narrow square slits. The whole structure is built of clay bricks bonded with lime mortar, and some irregular stones can be observed in limited areas. Brick average size is $0.30 \times 0.20 \times 0.04$ m^3 and average lime thickness is 0.035 m.

A comprehensive geotechnical report and foundation analysis is available. Outer walls and core are directly embedded in the soil, acting as foundation. The subsoil is made up of dark schists with a meteorization degree IV at ground level. It can be considered a compact granular soil, and its most representative mechanical parameter, the allowable soil stress, is 0.2 MPa.

A careful visual survey of the structure revealed severe damage such as: (i) irregular mortar-brick layout; (ii) no bonded masonry; (iii) poor quality of units and mortar; (iv) moisture; (v) loss of material; (vi) a variegated crack pattern — diffused, thin and passing-through cracks; (vii) local detachment of outer wythe; (viii) local reconstruction with different materials, stones or poor quality bricks. Most damage have to do with flaking of bricks due to deterioration. Significant cracks are located in the outer walls, at a height of 3 m. Thus, the south-western load-bearing wall exhibits passing-through crack, with an average opening of 0.04 m and a total length of 0.70 m. A depth crack appears in the inside face of the north-western wall, and other minor