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Laboratory testing and finite element simulation of the structural response of an adobe masonry building under horizontal loading

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ABSTRACT

This paper is concerned with the calibration and validation of a numerical modelling approach for adobe masonry buildings under horizontal loading. The paper first reviews the state-of-the-art in experimental and computational research of adobe structures and then presents results obtained from monotonic lateral loading laboratory tests on a 1:2 scaled unreinforced adobe masonry building. Through the experimental investigation conducted, useful conclusions concerning the initiation and propagation of cracking failure are deduced. In addition, damage limit states at different levels of deformation are identified. Experimental results verify that the response of adobe structures to horizontal loads is critically affected by weak bonding between the masonry units and mortar joints and by lack of effective diaphragmatic function at roof level. Based on experimental material data, a 3D finite element (FE) continuum model is developed and calibrated to reproduce the test structure's force–displacement response and mode of failure. An isotropic damaged plasticity constitutive law is adopted for the numerical simulation of adobe masonry and the use of appropriate modelling parameters is discussed. The FE analyses carried out reveal that the global structural behaviour is primarily influenced by the tensile response assigned to the homogenized masonry medium. Results show that, despite its generic limitations and simplifications, FE continuum macro-modelling can approximate the structural behaviour of horizontally loaded adobe masonry construction with sufficient accuracy. In order to enrich the available information on the seismic behaviour of adobe structures, the calibrated FE model is also subjected to time-history analysis using an accelerogram recorded during a real earthquake.

1. Introduction

Adobe masonry structures are encountered in almost every region of the world and are considered to possess significant historic and cultural value. At the same time, unreinforced adobe masonry is quite susceptible to seismic damage [1]. The strong seismicity of areas where a considerable number of earthen buildings exists (i.e. wider Eastern Mediterranean region, South Asia, South America) renders the study of the behaviour of adobe structures under horizontal loads essential. The development of structural analysis methods that account for the specific characteristics of adobe masonry is also required to facilitate the implementation of rational engineering assessment and design.

Up to date, several studies involving laboratory testing of full- and/or reduced-scale adobe structures have been conducted [2–19]. Emphasis has been primarily given on evaluating various repair/retrofitting techniques, rather than on providing extensive data, which can be exploited for the calibration and validation of numerical analysis tools. Researchers who have developed numerical models of adobe masonry structures [20–29] have mainly performed conceptual analyses aiming to obtain qualitative information regarding the response of typical traditional earthen buildings. Detailed comparisons between simulation results and physically measured aspects of structural behaviour (i.e. deformation, load-resistance) are rather limited [23–25]. This indicates that there is a need for adopting a more integrated research approach that will combine experimental and computational work on adobe masonry buildings, in order to develop reliable assessment procedures and analysis methods.

The present study aims to extend existing knowledge regarding the structural behaviour of adobe buildings by contributing towards the development of appropriate assessment procedures and analysis methods. Hence, it utilizes the results of large-scale laboratory tests to develop a finite element (FE) continuum macro-model capable of simulating the response of a horizontally loaded unreinforced adobe masonry building with sufficient accuracy. More specifically, for the purpose of validating the FE

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model, a 1:2 scaled replica of an existing single-storey traditional adobe building was constructed and subjected to monotonic static lateral loading tests. Masonry failure mechanisms (i.e. initiation and propagation of cracking) were recorded during the experimental procedure, while damage limit states at different levels of deformation were identified.

In the framework of the numerical investigation, a detailed 3D FE model of the scaled building was developed. This was used for performing non-linear analyses, aiming to macroscopically reproduce the general response of the structure under test. For the numerical representation of adobe masonry behaviour, a damaged plasticity constitutive law was adopted, while experimentally derived material data were used as input parameters. The validity of the numerical results was verified both qualitatively and quantitatively through comparisons with the experimental damage patterns and force–displacement curves. Numerical work did not however solely focus on the reproduction of the experimental results. A sensitivity analysis was also carried out to examine how the various modelling parameters affect the simulation of structural response. The scope of the paper extends to the use of the calibrated FE model for performing non-linear dynamic analysis, thus acquiring useful information on the seismic behaviour of adobe structures. Overall, this work represents a promising step towards the numerical modelling of the seismic behaviour of earthen constructions, while at the same time it identifies areas where further research is required.

2. Review of experimental and computational research on adobe structures

2.1. Experimental work

Most experimental data currently available regarding the response of adobe masonry construction has been obtained by examining model structures before and after the implementation of repair/strengthening interventions.

Systematic testing of unreinforced adobe masonry structures took place in the framework of various research projects undertaken by the Pontifical Catholic University of Peru. Relevant experimental work included static tilt tests on house modules [2], displacement-controlled cyclic tests on 'I'-shaped wall configurations [3] and shake table tests on single- [4–7] and two-storey [8] model buildings and vaulted structures [9,10]. In all cases, the response of unreinforced model structures was compared to that of reinforced ones (i.e. structures incorporating timber ring beams, cane rods, steel wire meshes, geogrids, fibre-reinforced polymer strips, tire straps, etc.).

Noticeable experimental research on the dynamic response of unreinforced adobe masonry buildings was also carried out during the Getty Seismic Adobe Project. In the first phase of this project, 1:5-scaled replicas of single-storey dwellings were subjected to impact hammer and shake table tests before and after repairing/strengthening [11]. In the second phase of the same project [12], dynamic excitations based on real accelerograms were imposed on larger (1:2 scaled) models. At this phase, in addition to unreinforced masonry structures, model buildings retrofitted with bond beams, horizontal/vertical straps, local ties, centre-core rods and wooden roof diaphragms were also examined.

Dowling [13] conducted shake table tests on 1:2 scaled 'U'-shaped wall units and complete buildings to examine the dynamic behaviour of unreinforced adobe masonry construction. Along with plain unreinforced masonry structures, models incorporating pilasters/buttresses, wire meshes, bamboo poles and timber ring beams were also constructed and tested in this study. The outcomes obtained were used for proposing retrofitting solutions.

More recently, a real-scale 'I'-shaped adobe wall was examined at Aveiro University [14]. Following a number of cyclic lateral loading tests, the cracks formed in the masonry were injected with lime mortar and a polymeric mesh was fixed on the surface of the wall. The repaired/retrofitted structure was subjected to further lateral loading tests.

Extensive literature on the response of strengthened/retrofitted adobe masonry buildings can also be found in [15–19], which present results from shake table tests and static horizontal loading tests on 1:1.5 [15], 1:2.5 [16], 1:3 [18], 1:5 [15] and 1:10 [17,19] scaled model structures.

The main conclusion derived from the aforementioned tests is that adobe masonry structures generally have limited capacity to resist horizontal loads. This is attributed to two factors: (a) poor bonding between the adobe bricks and the mortar joints, which reduces the tensile strength of the masonry [4,11,14], and (b) lack of diaphragmatic function at roof level, which precludes effective transfer of loads among the load-bearing walls [11,12]. Under seismic action, out-of-plane failure, either due to extensive cracking or due to detachment at cross-walls and overturning, prevails [4,11–13]. Integrated retrofitting systems can improve the poor seismic behaviour of unreinforced adobe masonry buildings, either by increasing their overall lateral resistance or by producing a confinement effect, which reduces the risk of brittle collapse [12–19].

2.2. Numerical modelling and analysis

In contrast to experimental work, computational research on adobe masonry structures has not been as rigorous. Despite the fact that advanced analysis methods have been extensively used for the simulation of conventional masonry structures (i.e. structures built with stone, fired clay bricks, concrete blocks, etc.), the application of numerical tools has not been meticulously studied in the context of earthen construction.

Simulation of masonry structures can follow a macro- or a micro-approach. In the macro-approach, either distinct macro-elements are used to represent individual piers and spandrels, or the masonry is treated as a fictitious homogeneous medium represented by continuum finite elements. In the micro-approach, the masonry unit–mortar interfaces are considered as potential crack/slip planes, while the building blocks and the mortar are either explicitly described (detailed micro-modelling) or represented by repeated expanded cellular units interacting at their boundaries (simplified micro-modelling).

Continuum FE models of adobe-wood buildings have been developed by Che et al. [20]. These were subjected to elastic time domain analysis, in order to examine their seismic response. Linear dynamic analyses by response spectra have also been conducted by Gomes et al. [21] on 3D models of unreinforced and reinforced adobe buildings.

Using experimental material data, Meyer [22] modified the Holmquist–Johnson–Cook model for concrete to capture the pressure and strain-rate-dependent non-linear behaviour of adobes. The formulated constitutive law was used for performing physics-based penetration simulations on adobe targets.

Non-linear static and dynamic simulations on FE continuum models composed of shell elements have been undertaken by Tarque et al. [23–25]. These studies focused on approximating the macroscopic behaviour (mode of failure, displacements, etc.) of structures tested in the laboratory. Modelling parameters were calibrated by matching numerical–experimental results. Both orthotropic smeared cracking and isotropic damaged plasticity constitutive laws were considered.

In addition to FE models of continua, Tarque et al. [23] examined 3D micro-models of adobe walls loaded in-plane. The authors assumed that the response of adobe bricks is elastic isotropic and