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Out-of-plane behavior of stone masonry walls: Experimental and numerical analysis

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HIGHLIGHTS

- Static cyclic out-of-plane testing of two 1:2 scaled unreinforced stone masonry walls.
- Non-destructive tests allowed estimating the mechanical properties of the masonry.
- Tests showed the influence of the masonry bond and the connection between the walls.
- The numerical macro-model approach accurately simulated the experimental results.
- The numerical model could be used to simulate different geometric configurations.

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ABSTRACT

Aiming at contributing to the better understanding of the out-of-plane behavior of unreinforced stone masonry structures, this paper presents the results of an experimental and numerical campaign performed on two U-shaped walls with different masonry bonds representative of Portuguese vernacular architecture. The experimental campaign included non-destructive tests for the material characterization and an out-of-plane cyclic loading test for the characterization of the out-of-plane response. A finite element numerical model was constructed, calibrated with the experimental results, which allowed performing a nonlinear parametric study to evaluate the most influential material and geometrical parameters in the out-of-plane behavior of stone masonry walls.

1. Introduction

Stone masonry is a traditional construction technique that can be observed in many regions throughout the world where stone is locally available. Many monuments and historical constructions were constructed in stone masonry, but also the vernacular buildings of many regions are frequently built with stone, see Fig. 1. Even though many of these examples have lasted until today, showing an outstanding endurance, stone masonry buildings typically show a poor performance when subjected to seismic actions, which leads to significant human and economic losses in case of occurrence of an earthquake.

Stone masonry is a heterogeneous material composed of stone units and joints, whose structural behavior depends on the individual properties of its components, as well as on the bond between them. Stone units vary widely in terms of material, size and shape. Besides, the mortar used for the joints can be made of many different materials (clay, lime, cement-based, etc.). Additionally, stone masonry is usually composed of several leaves and the connection among them also influences its behavior. Thus, there can be a great number of combinations, constituting stone masonry types showing a very different mechanical behavior, but, generally, an almost null tensile strength is common to most of them. Moreover, vernacular buildings are particularly built using low cost and simple construction technology. As a result, stone masonry buildings can

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Fig. 1. Example of typical Portuguese stone masonry constructions.

show insufficient construction and material quality to withstand seismic load because of the use of round unshaped stones, absence of connection between wall leaves, poor adhesion between stone and mortar, presence of voids, or lack of proper connections between walls and diaphragms or between perpendicular walls [48]. These deficiencies cause stone masonry buildings to commonly show different types of premature local out-of-plane failure mechanisms before a global seismic response governed by the in-plane capacity of the walls is activated.

Façade walls are usually the most vulnerable elements in stone masonry buildings precisely because of the previously noted lack of structural integrity due to a poor connection between structural elements, namely with the perpendicular walls and diaphragms. This is the reason why the out-of-plane collapse of the façade walls has been recurrently observed in past earthquakes [52,7,17,32,9,47,53,46,50,10,27]. Fig. 2 shows some of these typical out-of-plane collapses of the façade observed after 2009 L'Aquila earthquake in Italy.

Despite the growing research interest on the study of the out-of-plane behavior of stone masonry walls in the recent years, there is still a limited understanding due to its complexity. Thus, experimental research on the seismic behavior of traditional stone masonry structures is relevant because it can contribute to the preservation of the vernacular architectural heritage. The experimental characterization of the out-of-plane behavior of stone masonry walls has been carried out either in the laboratory or *in-situ*, and it can provide relevant results in terms of maximum lateral resistance, stiffness, deformability and crack propagation. The material and mechanical characterization can also eventually help in the development and calibration of numerical models to simulate the response of other structures with different configurations.

Several examples of experimental laboratory works aimed at the assessment of the out-of-plane seismic performance of masonry structures can be found in the literature. Shaking table tests have been carried out on reduced scale masonry buildings [44,8,55], full scale masonry buildings [41,15,15,16,34], on reduced scale structural elements [58] and on full scale structural elements [1,11,29,30]. In these cases, the simulation of the seismic action is performed in a realistic way. Results of static cyclic tests are also available in the literature, where the seismic action is simulated in a simplified way through: (1) airbags [31,19,20,43], reproducing the seismic loading as a set of distributed inertia forces at the wall; or (2) hydraulic actuators [26], imposing the seismic load as a linear load at the top. In general, laboratory testing requires the construction of new specimens using new materials with the aim of replicating the originals

Therefore, an alternative to laboratory experimental out-of-plane tests can be the *in-situ* testing of masonry structures, which has an advantage over laboratory tests because the experiments can be directly performed on the original masonry walls. That is why, whenever is possible, *in-situ* testing is preferred, since it provides information about the original masonry walls in terms of: (a) materials properties; (b) geometry and morphology of the wall; and (c) mechanical behavior.

As an example of the *in-situ* characterization of the out-of-plane behavior of masonry structures, Ingham & Ismail [33] used a set of airbags to apply a cyclic uniformly distributed load to two walls from an historic New Zealand house. The walls were previously reinforced using near surface mounted twisted steel bars (NSM-TS) in order to assess the performance of this reinforcing technique on walls subjected to out-of-plane loading. A series of similar out-of-plane cyclic tests were also performed in the laboratory on two walls constructed replicating those from the original historic constructions, aiming at comparing the results from the *in-situ* experimental campaign. An extensive experimental work on out-of-plane *in-situ* testing on stone masonry walls was also developed on typical walls from Azores island, in Portugal, following the 1998 earthquake [12,3,13,14]. Another example of out-of-plane *in-situ* tests is the work carried out by Derakhshan et al. [21], on

Fig. 2. Examples of common out-of-plane earthquake damage patterns in stone masonry buildings after 2009 L'Aquila earthquake.