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Experimental evaluation of out-of-plane capacity of masonry infill walls

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ABSTRACT

Infill masonry (IM) walls are considered to be non-structural elements but, when subjected to earthquakes, they tend to interact with the surrounding RC (reinforced concrete) frames, which can result in different failure modes depending on the combination of the in-plane and out-of-plane behaviour. Therefore, the contribution of IM panels should be considered in the structural response analysis of existing buildings, for which an understanding of the out-of-plane non-linear behaviour of IM walls is of paramount importance in order to develop efficient strengthening solutions to prevent collapse and improve their performance in future earthquakes, and consequently reduce their seismic vulnerability. In order to obtain further knowledge of the out-of-plane response of IM panels, a study of full-scale IM walls was carried out with the realization of three experimental (cyclic and monotonic) out-of-plane tests with and without previous in-plane damage. The experiments, material characterization and the test set-up will be described in this paper as well as presenting and discussing the main test results, namely in terms of hysteretic force–displacement curves, damage evolution, stiffness degradation and energy dissipation.

1. Introduction

In recent years, interest has increased in the study of infill masonry (IM) walls, namely in their influence on the seismic response of existing buildings. The contribution of the presence of IM to a building's seismic performance can be favourable or unfavourable, depending on a series of phenomena detailing aspects and mechanical properties, such as the relative stiffness and strength between the frames and the IM walls, and the type of connection between the IM and the structures [1–7].

From the surveys of damaged and collapsed reinforced concrete (RC) buildings in recent earthquakes, a large number of buildings that suffered severe damage or collapse had their poor performance associated with the influence of the infill panels [8,9]. In some RC buildings subjected to seismic actions it is possible to observe that the major part of the structural elements has satisfactory behaviour with slight or no damage; however, their IM walls suffer much damage (in-plane or out-of-plane). Detachment of the IM panel from the surrounding RC frame, diagonal cracking as well as sliding cracking in the centre of the panel, shown in Fig. 1a–c are frequently observed.

Moreover, the non-balanced in-plane distribution of infill panels can introduce global torsion in buildings, which can induce larger demands on columns that were not considered in the original design [10–12].

Three main mechanisms associated with the presence of IM walls have been reported. One is associated with the short column mechanism, where IM walls leave a short portion of the column clear, concentrating larger demands in a short element; another is related to the absence of panels on the ground floor, inducing a sudden change in the storey stiffness and strength in height, leading to a soft-storey mechanism [13]. The third and one of the most critical failures is the out-of-plane infill, illustrated in Fig. 2. One of the major factors that causes out-of-plane instability and poor performance is the deficient/insufficient support-width of the RC beams and/or slabs, normally adopted to minimize the thermal-bridge effect, with no connection between the interior and the exterior panels and, finally, no connection to the surrounding RC frames [9,14].

It is consensual that further and deeper knowledge is required of the out-of-plane behaviour of IM walls to develop effective retrofit strategies that prevent this type of collapse and consequently protect the buildings' users' safety, as well as that of people near the building. The study of this type of collapse mechanism is also important to support the development of accurate numerical models that represent the expected behaviour of IM walls subjected to out-of-plane loadings, combined or not with in-plane loadings.

Thus, the experimental test appears to be an excellent tool that allows the study of IM walls subjected to static or dynamic cyclic

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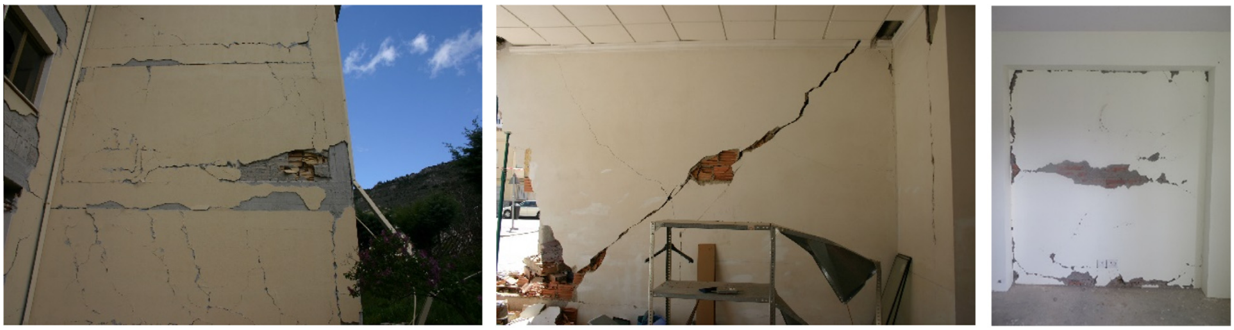
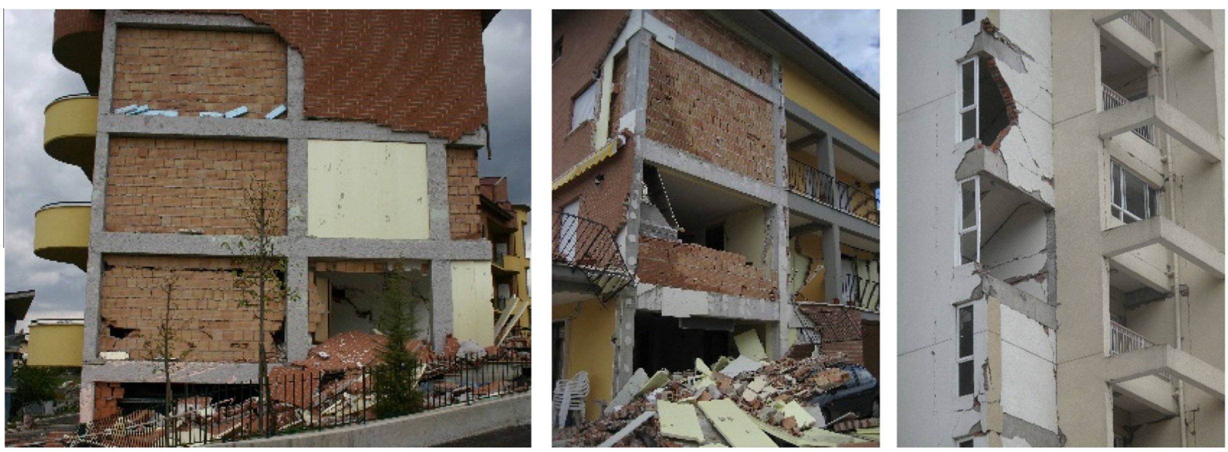


(a) (b) (c)

Fig. 1. Typical damage observed on in-plane IM walls: (a) detachment of the surrounding RC frame in the L'Aquila (Italy) earthquake, (b) diagonal cracking in Lorca (Spain) and (c) in the Nepal earthquake.



(a) (b) (c)

Fig. 2. IM walls out-of-plane collapse: (a) and (b) in the L'Aquila earthquake, and (c) in the Nepal Earthquake in 2015.

experimental tests combining different types of test variation, such as: evaluation of the out-of-plane performance with different in-plane damage levels, variations in the dimensions of the IM walls, and different types of masonry bricks. However this type of experimental test is difficult to perform as it requires complex experimental set-ups with sufficient capacity for large samples. Some experimental studies have been carried out in order to characterize the out-of-plane performance of the infill panels considering and ignoring previous in-plane damage [15–17]. It was observed that the out-of-plane capacity of the IM walls is reduced with the increase in in-plane demands, leading to the conclusion that further experimental investigations, mainly of specimens representative of the country's building stock, are of extreme importance.

From previous works and based also on the results provided by the experimental tests some important direction can be withdrawn for the future, and in particular can be fundamental to earthquake prone countries, namely: (i) the structural engineers should take into account with the structural contribution of this non-structural elements in the buildings response when subjected to earthquake loadings; (ii) With the experimental characterization of the IM walls it is possible to develop some strengthening strategies that could reduce their vulnerability, and thus save people's lives and decrease the level of damages that this non-structural elements are subjected to; (iii) new guidelines regarding the IM walls construction process can be drawn to improve their seismic performance, and thus eliminate some factors that increase their in-plane and/or out-of-plane seismic vulnerability (such for example construction of infill panels disconnected of the surrounding RC frame, etc.); (iv) The experimental data results can be used to calibrate numerical models, and thus assess the seismic vulnerability of existing and/or new buildings considering the IM walls real and expected behaviour when subjected to an earthquake.

Based on this motivation, an experimental campaign was undertaken with the main goal of characterizing the out-of-plane behaviour of infilled RC frames. Full-scale experimental tests were undertaken at the Laboratory of Earthquake and Structural Engineering – LESE, with the geometry based on a previous statistical study conducted into Portuguese RC building stock, namely buildings constructed in the 1960s and 1970s [18]. The results of the experiments comprising three out-of-plane tests (with and without previous in-plane damage) will be presented and also discussed in terms of hysteretic force–displacement curves, damage evolution, cracking pattern and displacements profiles.

2. Experimental tests

2.1. Experimental tests overview and specimen descriptions

The present experiments comprised three out-of-plane tests of full-scale infilled RC frames, two of them without previous in-plane damage and one with previous in-plane damage. The general dimensions of the specimens were selected as 4.80 × 3.30 m and the cross sections of the RC columns and beams were 0.30 × 0.30 m and 0.30 × 0.50 m, respectively, which are representative of those existing in the Portuguese building stock [18]. Fig. 3 shows the RC infilled frame geometry, as well as the corresponding