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Characterization of the out-of-plane behaviour of full-scale masonry infill walls with and without previous in-plane damage: experimental study

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Abstract

The seismic performance of the infill masonry (IM) walls is characterized by the interaction with the surrounding reinforced concrete (RC) frames, which can result in different failure modes depending on their in-plane and out-of-plane behaviour. It is known that the out-of-plane capacity of the IM walls is conditioned by the existence of previous in-plane damage that could decrease significantly their strength and stiffness, as well as the reduced support-width on RC beams and/or slabs adopted to minimize thermal bridges effect, or the absence of connection between the infill panel and the surrounding RC frame can result in a poor out-of-plane performance. However, in the literature the number of experimental studies regarding to IM walls subjected to out-of-plane loadings, combined or not with in-plane damage is reduced. For this an experimental testing campaign of full scale IM walls was started at the Laboratory of Earthquake and Structural Engineering – LESE by performing three experimental (cyclic and monotonic) out-of-plane tests with and without previous in-plane damage. The dimensions adopted for the specimens are representative of those existing in a large portion of the Portuguese building stock according to recent studies. The experimental campaign and test setup will be described as well as the experimental tests' results will be presented and discussed in the manuscript in terms of hysteretic force-displacement curves and damage evolution.

Keywords: infill masonry, static cyclic test, out-of-plane behaviour, previous in-plane damage, Force-displacement, damage evolution

1. Introduction

Typically the infill masonry (IM) walls are considered non-structural elements, however when subjected to earthquake loadings they tend to interact with the surrounding reinforced concrete (RC) elements and the contribution of their presence 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, the type of connection between the IM and the structures, etc. [1-7].

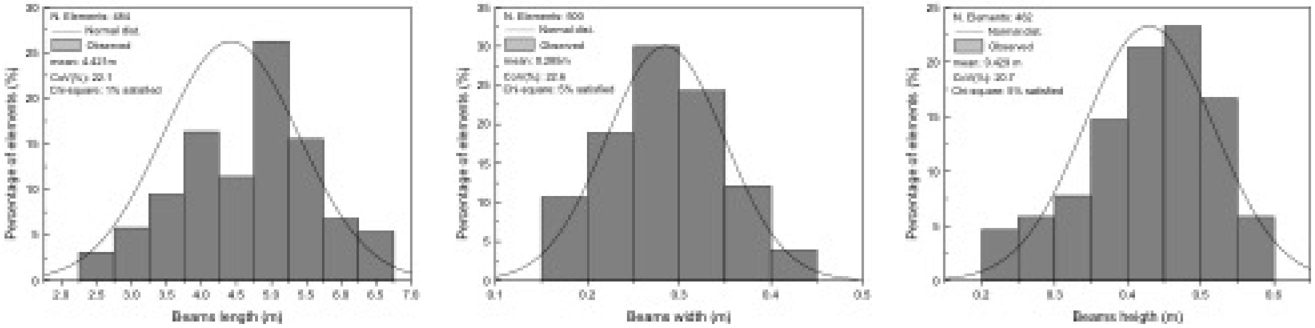
Survey reports after recent earthquakes recognize the important contribution of the IM walls in structural response of the buildings and indicate that a large number of buildings that suffered severe damage or collapse had their poor performance associated with the influence of the infill panels [8, 9]. The common types failures observed in the infill walls can be distinguished in two different ways: i) global behaviour of the building that are associated with irregular distribution such in terms of height and/or plan and result in soft-storey mechanisms, torsion problems or can be associated to the disposition of the openings that consequently introduce high shear stresses to the adjacent columns which can lead to their failure/collapse; ii) local behaviour of the IM wall that can be distinguished as caused by in plane loadings (detachment of the panel from the surrounding RC frame; diagonal cracking, shear-friction failure and corner crushing), out-of-plane loadings (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. This out-of-plane collapse of the infill walls are considered one of the most critical failures such it is a risk for the buildings users and surrounding, it increases significantly the costs associated to the repair/rehabilitation of the damaged building and finally this type of collapse could introduce stiffness irregularity and consequently lead the building to the formation of a collapse mechanism.

It is consensual that further and deeper knowledge regarding the infills out-of-plane behaviour is required to develop effective retrofit strategies that prevent this type of collapse, to develop 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.) and finally 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. With this aim 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 1960's and 70's [10]. 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. General overview of the experimental campaign

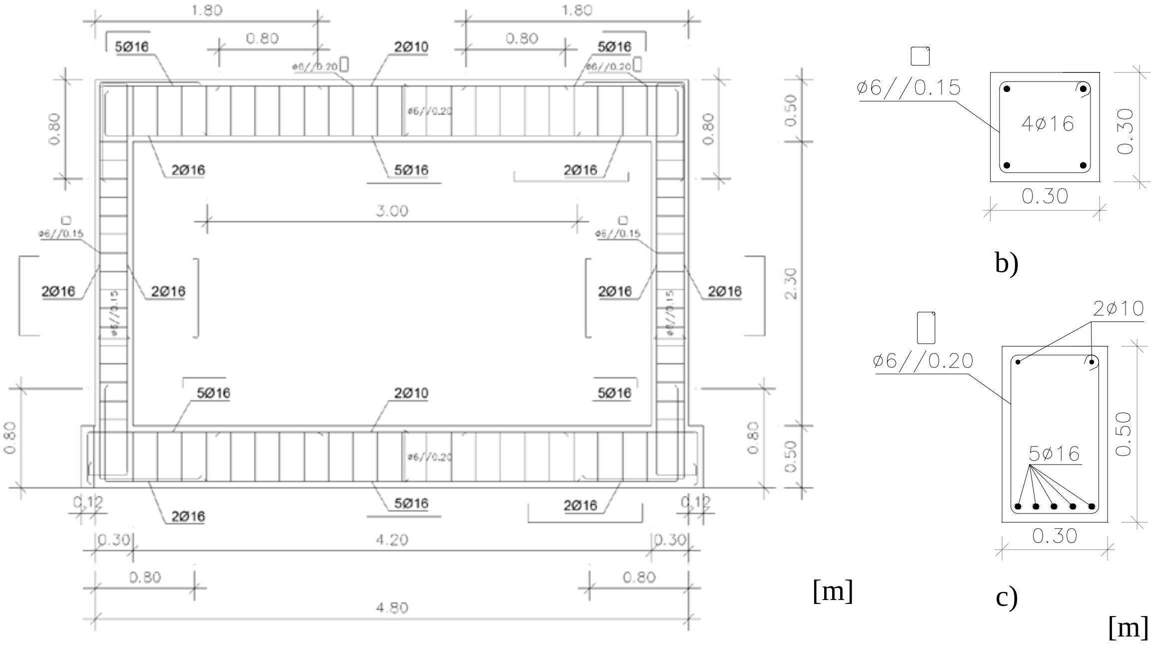
2.1 Specimens description

The present experimental campaign is composed by 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 4.80x3.30m and the cross sections of the RC columns and beams were 0.30x0.30m and 0.30x0.50m, respectively. This dimensions were found to be representative of those existing in the Portuguese building stock [10], in the sequence of a statistical study performed on 80 existing RC buildings in Portugal where was collected information of more than 300 RC elements (beams and columns) and 1500 IM walls. In Fig. 1 is illustrated some of the results obtained regarding the beams length, width and height. Fig. 2 shows the RC infilled frame geometry, as well as the corresponding column and beam dimensions and reinforcement detailing (Fig. 2b and c). All infill panels have equal geometry with in-elevation dimensions of 2.30x4.20m made of horizontal hollow clay bricks, as usually found in the most common masonry in Portugal. No reinforcement was used to connect the infill panel and the surrounding RC frame.



a) b) c)

Fig. 1 – Geometric characterization of the Portugal building stock: a) RC beams length; b) RC beams width; and c) RC beams height.

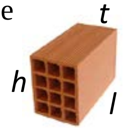


a)

Fig. 2 – Infilled RC frame specimen dimensions (in meters): a) General dimensions; b) column; and c) beam dimensions and reinforcement detailing.

As previously stated, three infill panels were built (denoted as Inf_01, Inf_02 and Inf_03), all having an external leaf (150mm thick) aligned with the external side of the RC beam. For the panel Inf_03, an internal leaf, 110mm thick, was added aligned with internal side of the beam, leaving a hollow thickness of 40mm. This double-leaf panel was first tested for in-plane cyclic displacements, after which the internal leaf was removed, leaving the external leaf to be tested under the same out-of-plane loading conditions as for panel Inf_02. A summary of the experimental tests and corresponding main characteristics are illustrated in Table 1.

Table 1 – Summary of the experimental campaign..

Test number	Previous in-plane drift (%)	Type	Number of leaves	Brick unit size l x h x t (mm) 
Inf_01	-	Fully infilled	1	300x200x150
Inf_02	-		1	300x200x150
Inf_03	0.5%		2(*)	300x200x150 (ext.) 300x200x110 (int.)

2.2 Material characterization

The selected masonry typology represents the common clay blocks used in Southern Europe with horizontal perforations and the geometric properties illustrated in Fig.3. Two different brick typologies were adopted, varying only in the brick thickness. For the specimens Inf_01 and Inf_02 brick type A was used, and for Inf_03 both brick type A and brick type B were used with type B removed for the out-of-plane test.

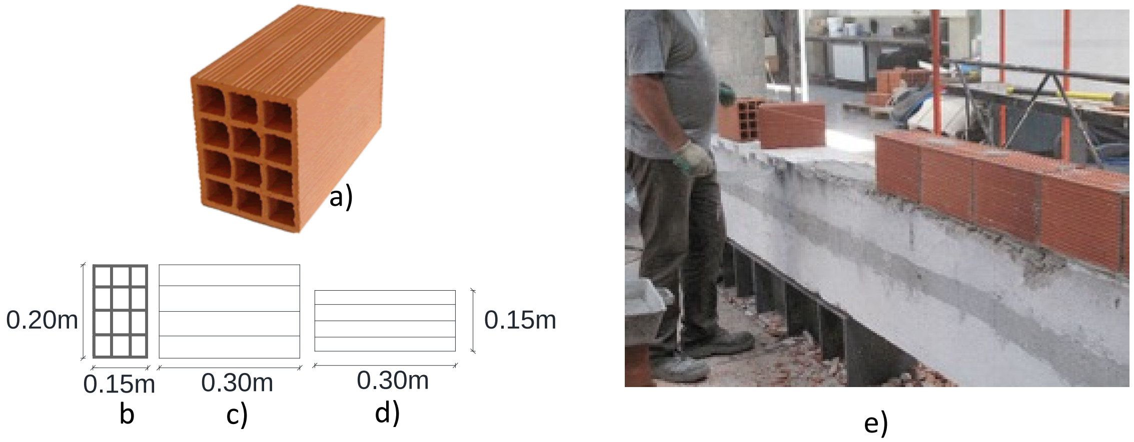


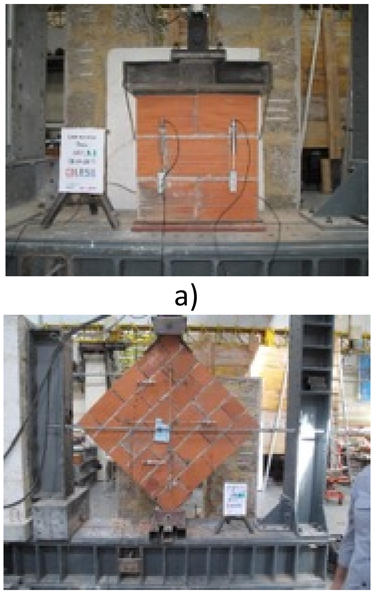
Fig. 3 – Masonry brick type a) General view; b) Transversal section dimensions; c) lateral dimensions; d) top dimensions and e) Construction process of the IM wall.

A traditional mortar type M5 (Ciarga) was considered a suitable choice with respect to the normal practice of the Portuguese construction industry in the 1970s. The panels were constructed after the full hardening of the RC frame. The thickness of both the adopted vertical and the horizontal bed joints was 1cm. Full contact between the infill panel and the surrounding RC elements was considered to be achieved by filling the vertical gaps between the infill and the top horizontal gap with mortar.

Further characterization tests were carried out on the mechanical properties of the IM wallets. For this, seven samples were subjected to compression strength tests and six samples to diagonal tensile strength tests, as illustrated in Fig. 4a and b respectively. The most common damage observed was top or bottom crushing and diagonal cracking of the wallets subjected to vertical compression strength tests and diagonal compression tests respectively. A mean compression strength of fm=0.531MPa with vertical elasticity modulus of Em=1417.6MPa were found. From the diagonal tensile strength tests was obtained the mean value of fm=0.303MPa.The tests results are summarized in Table 2.

Table 2 – Material characterization tests of IM wallet specimens: compression strength tests and Diagonal tensile strength tests on IM wallet specimens.

	Compression strength test		Diagonal Tensile strength test
Brick Type Size (mm)	300x200x150		300x200x150
Sample	$f_{m,}$ (MPa)	Ei (MPa)	$f_{md,}$ (MPa)
Mean (MPa)	0.531	1417.6	0.303
S.D.	0.095	345	0.059
C.O.V.	0.180	0.240	0.190
Characteristic Value (MPa)	0.442	-	-



a)

b)

Fig. 4 – IM wallets characterization tests a) Compression strength tests; b) Diagonal tensile strength tests.

2.2 Test setup description

The out-of-plane test consisted of the application of a uniformly distributed surface load through a system composed of seven airbags, reacting against a self-equilibrated steel structure, as shown in Fig. 5. The application of a uniform out-of-plane loading pretends (as was observed) to globally mobilize the out-of-plane response of the IM wall. In the literature similar out-of-plane load distribution adopted by other authors can be found [11, 12]. This reaction structure is composed of five verticals and four horizontal alignments of rigidly connected steel bars, in front of which a vertical wooden platform is placed to resist the airbag pressure and transfer it to the steel reacting grid elements. Thus, 12 steel threaded rods, crossing the RC elements in previously drilled holes, were used to equilibrate the reaction force resulting from the pressure applied by the airbags in the infill panel. The steel rods were strategically placed to evaluate the load distribution throughout the entire infilled RC frame resorting to load cells attached to each rod, which allowed continuous measurement of the forces transmitted to the reaction structure to which the rods were directly screwed. On the other extremity of each tensioned rod, appropriate nuts and steel plates were used to anchor the rod and apply its reaction force to the concrete surface by uniformly distributed normal stresses, thus avoiding load concentration on the RC elements crossed by the rods.

In each column, the axial load was applied by means of a hydraulic jack inserted between a steel cap placed on the top of the column and an upper HEB steel shape, which, in turn, was connected to the foundation steel shape resorting to a pair of high-strength rods per column. Hinged connections were adopted between these rods and the top and foundation steel shapes; the axial load actually applied to the columns was continuously measured by load cells inserted between the jacks and the top of each column, which was paramount in performing the in-plane tests.

The pressure level inside the airbags was set by two pressure valves which were controlled according to the target and measured out-of-plane displacement of the central point of the infill panel (the control node and variable) continuously acquired during the tests using a data acquisition and control system developed in the National Instruments LabVIEW software platform [13]. Prior to the experiments, calibration of the whole system was undertaken; this consisted of comparing the sum of the load cell forces with the airbag pressure resultant force (the pressure multiplied by the theoretical loaded panel area), in order to obtain the variation of load distribution, i.e. indirectly the actually loaded area, with the increase in distance between the steel reaction structure and the surface loaded panel. This calibration was achieved by inserting a vertical wooden panel supported in wood beams reacting against the RC top and bottom beams, thus without involving the brick masonry panel.

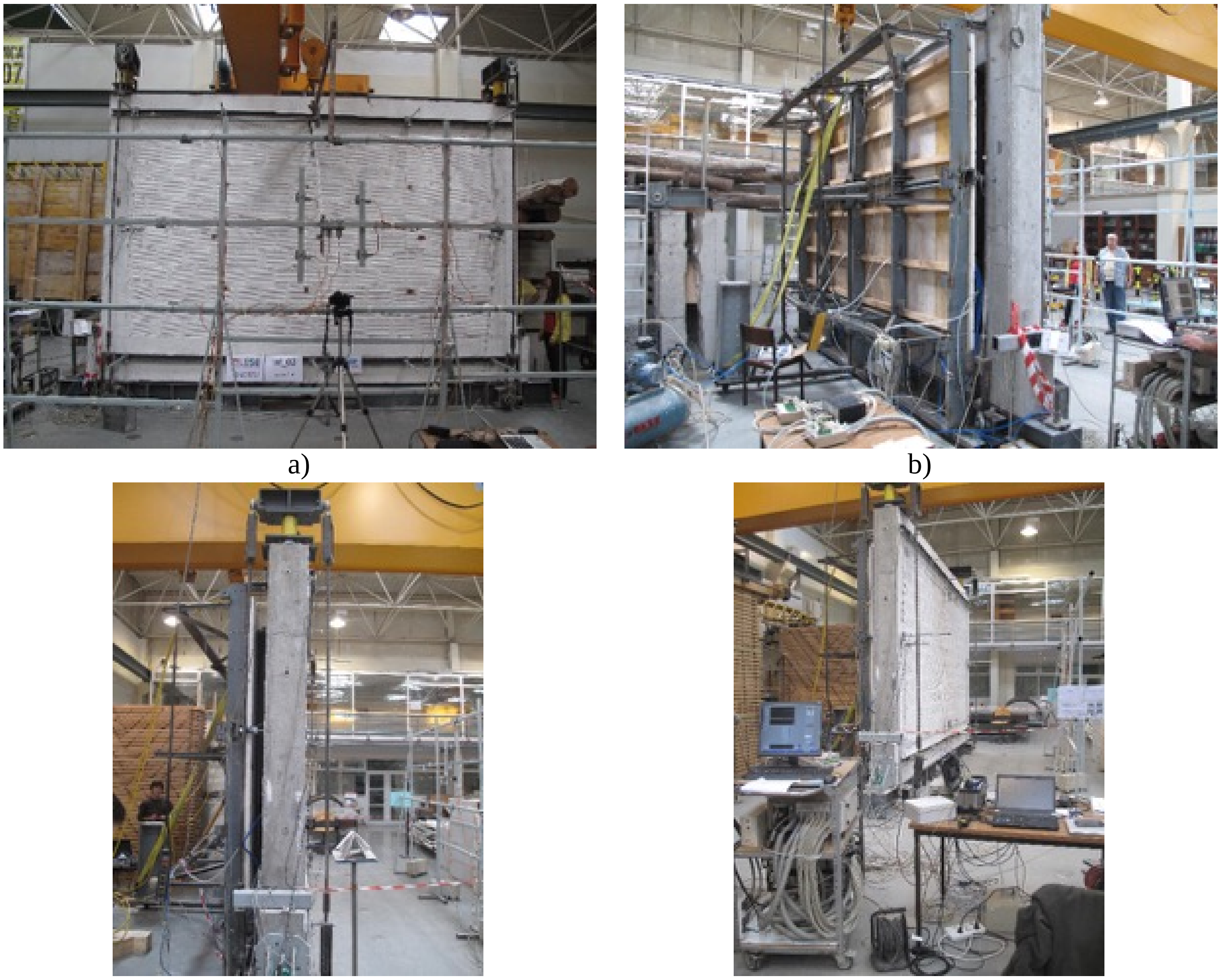

a) b) c) d)

Fig. 5 – Out-of-plane experimental test set-up: a) front view; b) back view; c) lateral view; and d) General view of the acquisition system disposition during the test.

2.3 Instrumentation

The instrumentation of the experimental tests comprised a total of 23 displacement transducers, among linear variable displacement transducers (LVDTs) and draw wire transducers (DWTs), as illustrated in Fig. 6. The transducers were divided into 3 different groups according to the corresponding measurement objective: i) IM wall out-of-plane displacements (13 DWTs), ii) out-of-plane rotation between the infill panel and the surrounding RC frame (8 LVDTs) and iii) out-of-plane displacements of the RC frame (2 LVDTs).

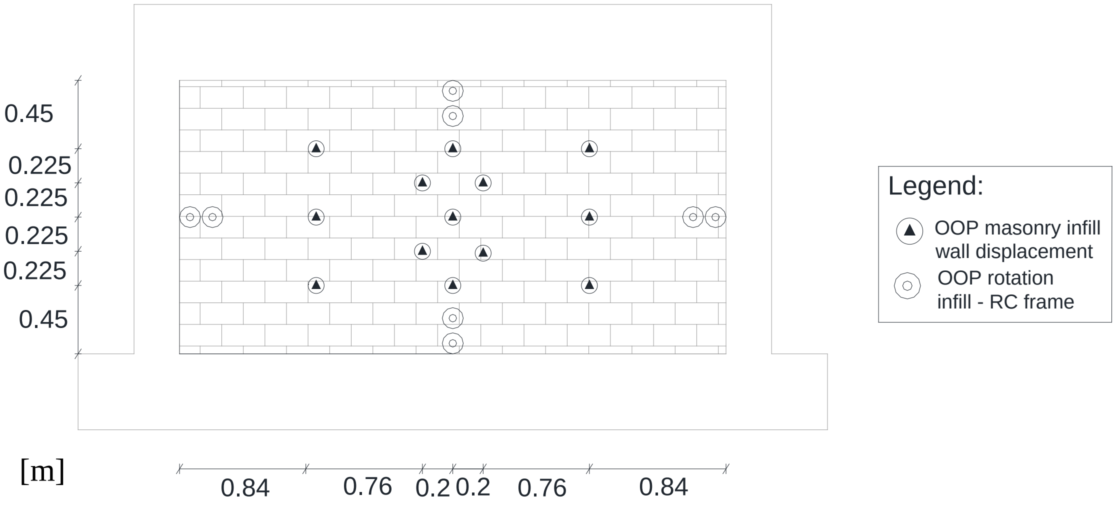
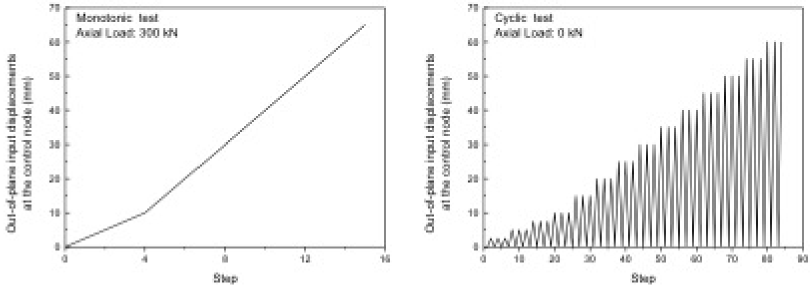


Fig. 6 – Layout of the out-of-plane test instrumentation (in meters).

2.3 Loading condition

As previously stated, the aim of the present experiments is to better understand the out-of-plane behaviour of IM walls, particularly when subjected to previous in-plane damage. In addition, the assessment of the influence of the RC column axial load application in the out-of-plane response was made possible by imposing an axial load of 300kN on each RC column during the test on Inf_01 and no axial load during tests on Inf_02 and Inf_03.

The third test Inf_03, comprising a double-leaf panel, was first subjected to an in-plane drift of 0.5%, and then the interior panel was removed and the damaged external wall was subjected to the out-of-plane test. The Inf_01 test was carried out by imposing monotonic increasing out-of-plane displacements in the IM panel. With regard to the Inf_02 and Inf_03 tests, cyclic out-of-plane displacements were imposed on the IM wall with steadily increasing displacement levels, targeting the following nominal peak displacements (in mm): 2.5; 5; 7.5; 10; 15; 20; 25; 30; 35; 40; 45; 50; 50; 55; 60; 65 and 70, as illustrated in Fig. 7. Three cycles were repeated for each lateral deformation demand level at the control node chosen as the central point of the IM wall where concentrated deformation is expected.



a) b)

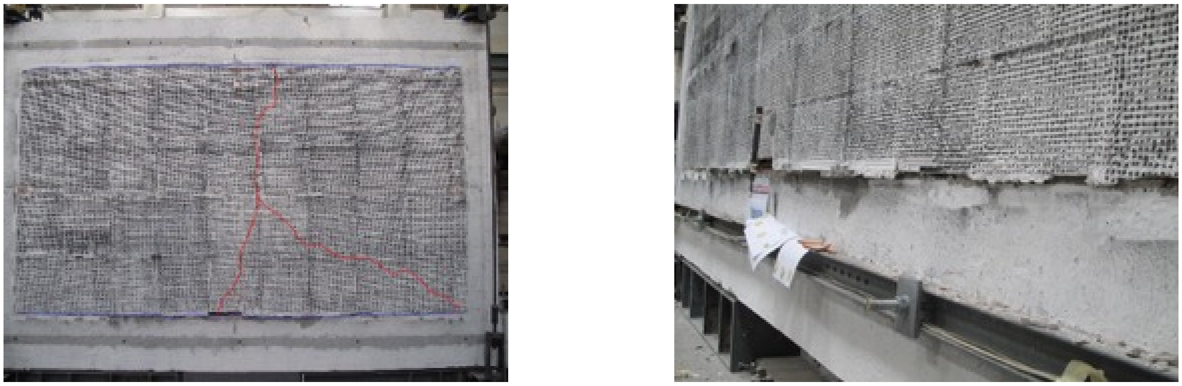
Fig. 7 – Loading condition for: a) monotonic test Inf_01 and b) cyclic test Inf_02 and Inf_03.

3. Experimental results

This section presents the experimental results of the IM walls out-of-plane tests based on: i) cracking pattern and failure mode observed during the tests; ii) shear-drift hysteretic curves where some parameters are discussed as initial stiffness, maximum strength, strength degradation; and finally c) maximum strength. For a better comparison the results all the three IM walls will be presented individually and globally, deducting the influence of the application a monotic or a cyclic out-of-plane loading and also the effect of the previous in-plane damage in the out-of-plane capacity of the wall.

3.1 Cracking pattern and failure mode

The final cracking shape of Inf_01 was majority vertical and it was also observed detachment between the infill panel and the surrounding RC frame in the top and bottom joints as illustrated in Fig. 8. However, the Inf_02 test exhibited a trilinear cracking pattern with deformation concentrated in the mid-point of the wall, with slight cracking in the top joint, as illustrated in Fig. 9. In the third test with previous in-plane damage (Inf_03), it was only observed the detachment between the infill panel and the surrounding top beam and columns, a typical rigid body behaviour, illustrated in Fig. 10.



a) b)

Fig. 8 – Inf_01: a) Cracking pattern; and b) Detachment observed between the panel and the bottom beam.

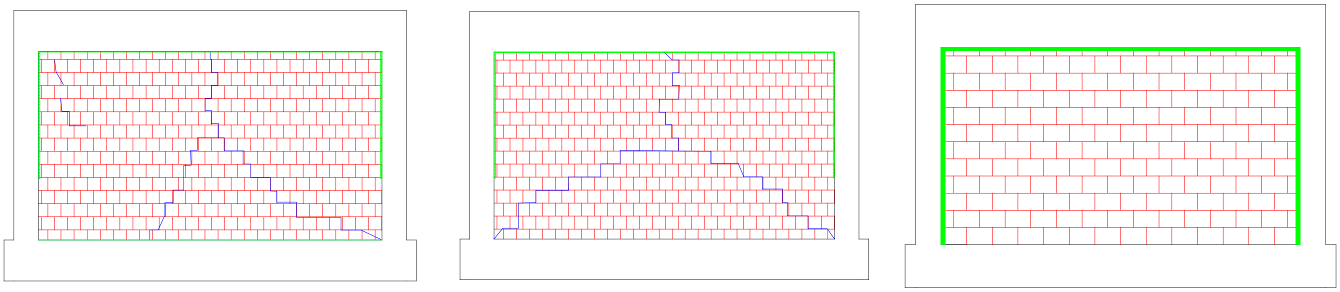
a) b)

Fig. 9 – Inf_02: a) Cracking pattern; and b) Triliear cracking pattern observed in the center of the panel.

a) b) c)

Fig. 10 – Inf_03: a) and b) Lateral view of the damage observed; and c) detachment of the infill panel from the surrounding RC frame as typical rigid body behaviour.

The final damage patterns of all tests are presented in Fig. 11, and show several differences between the tests with and without previous in-plane damage, which allow to conclude that the previous in-plane damage changes significantly the infill panel behaviour by increasing substantially their vulnerability under out-of-plane loadings.

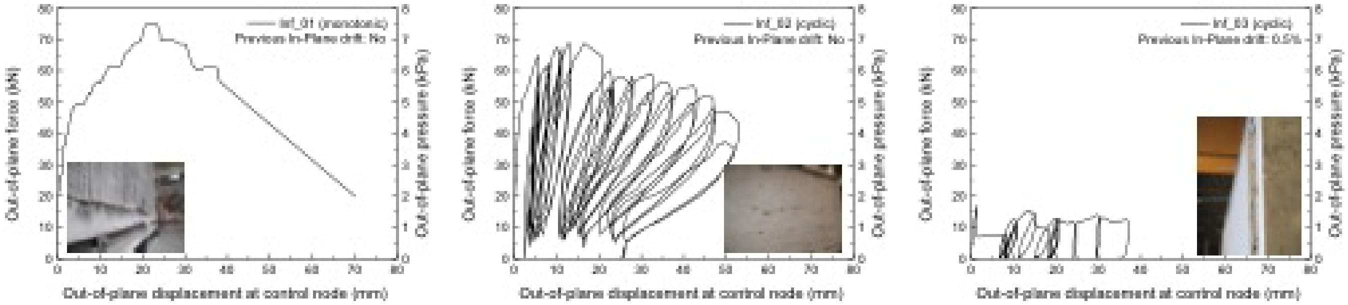


a) b) c)

Fig. 11 – Global test results cracking pattern: a) Inf_01, b) Inf_02 and c) Inf_03.

3.2 Shear-drift hysteretic behaviour

Through comparison between the force-displacement hysteretic curves plotted in Fig. 12, a significant difference between the test results, with and without previous in-plane damage can be observed, namely: a) the maximum strength was almost four times higher for the tests without previous in-plane damage and for higher out-of-plane drift values; b) the initial stiffness was significantly affected by the introduction of the in-plane damage, that of the test with previous in-plane damage (Inf_03) being almost 30% lower than the original IM walls; c) a significant maximum strength reduction was found in the tests without the previous in-plane damage, which was not verified in Inf_03.



a) b) c)

Fig. 12 – Force-displacement hysteretic curves: a) Inf_01, b) Inf_02 and c) Inf_03.

3.3 Maximum out-of-plane strength and displacement profiles

From the shear-drift curves it was measured the maximum strength of each test, plotted in Fig. 13 and it can be observed that the maximum strength of the Inf_01 was 5% higher than Inf_02, and both together reached four times higher maximum strength than the third one Inf_03. The out-of-plane displacement profiles of both IM walls were measured during the experiment along three different alignments a) left, b) center and c) right and at five different heights (h1=0m; h2=1/3hwall; h3=1/2hwall; h4=2/3hwall and h5=hwall, where hwall is the panel height), with the main objective of characterizing the evolution of the displacements during the experiment and are plotted in Fig 14. A significant difference can be seen between the Inf_01 and Inf_02 responses; in the main, displacements of Inf_02 are concentrated in the middle of the wall, particularly focusing on the center alignment, and the Inf_01 displacements are similar along the panel height. Regarding the third test it can be observed in the three alignments that the out-of-plane displacement is uniform through the panel height, explained by the failure mode of the wall.

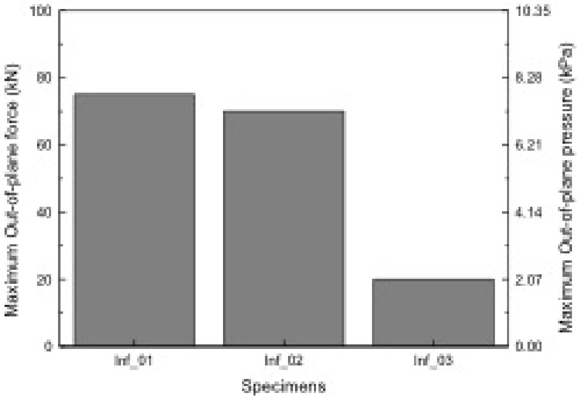


Fig. 13 – Total energy dissipated: a) Uniaxial tests; and b) biaxial tests.

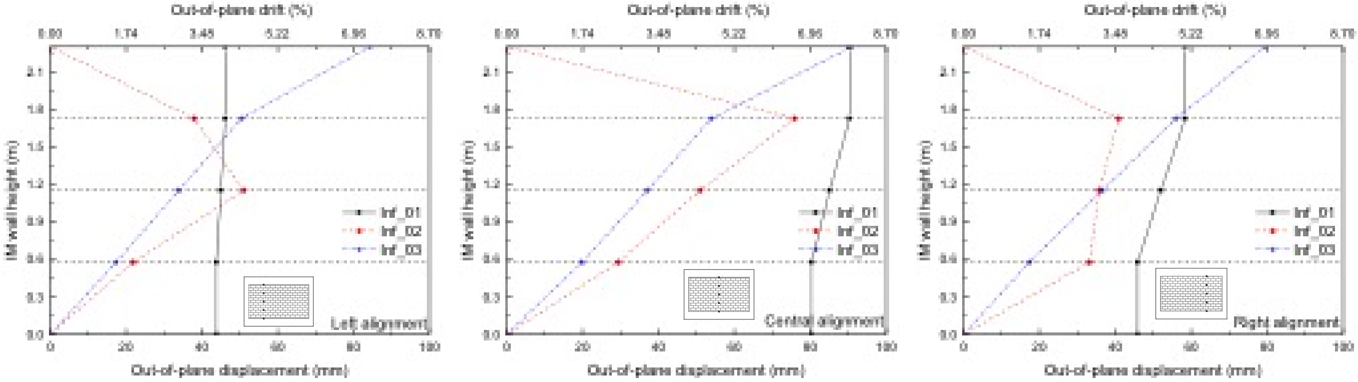


Fig. 14 – Global test results out-of-plane displacement profile: a) Inf_01, b) Inf_02 and c) Inf_03.

5. Conclusions

This manuscript presents an experimental campaign carried out at the Laboratory of Earthquake and Structural Engineering - LESE in order to study the out-of-plane behaviour of IM walls, and the influence of the previous in-plane drift in their out-of-plane response. For this, three full-scale infill panels representative of those existing in the Portugal building stock were built and were subjected to out-of-plane loadings (monotonic and cyclic), with and without previous in-plane drift. For the application of the out-of-plane loading was developed an innovative self-equilibrated steel structure that supports the reaction of the application of the out-of-plane pressure in the wall by nylon airbags.

A significant difference was found between the test results, with and without previous in-plane damage, namely: a) the maximum strength was almost four times higher for the tests without previous in-plane damage and for higher out-of-plane drift values; b) a significant reduction in the initial stiffness was observed in the test with previous in-plane damage when compared with the others; c) a significant maximum strength reduction was found in the tests without the previous in-plane damage, which was not verified in Inf_03. The failure modes observed in each of the tests reveal a different out-of-plane behaviour of the IM walls with and without previous in-plane damage. The tests on original IM walls (Inf_01 and Inf_02) showed vertical cracking, with detachment between the infill panel and the surrounding RC frame in the top and bottom joints. In the Inf_02 test wall, trilinear cracking was observed with deformation concentrated in the middle point of the wall, with slight cracking in the top joint. For the test with previous in-plane damage, detachment was observed between the infill panel and the surrounding top beam and columns, and typical rigid body behaviour was found.

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