16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3860

Registration Code: S-Y1463091800

Experimental characterization of masonry walls subjected to in-plane and out-of-plane loadings – Challenges and main features for the future

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Abstract

The masonry construction is one of oldest construction techniques and more used in all over the world. However, the structural response of masonry structures is complex and the knowledge concerning to their response to seismic events, or even regarding to their mechanical behaviour is still limited. An increasing interest on the experimental testing of this type of structures, particularly in the masonry walls performance, has been observed during the last years, to support better understanding of structural behaviour under earthquake loading, with emphasis on numerical model calibration, development of efficient techniques for seismic protection and/or resilience improvement of such type of structural elements. In the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of University of Porto a large experimental campaign was conducted during the last decade to characterize the seismic response of masonry walls. The out-of-plane response characterization of different type of masonry walls was performed by performing tests by applying distributed or point out-of-plane loadings such through the use of airbags or even by a hydraulic actuator. Furthermore, in-situ experimental tests were performed in existing stone masonry walls in existing buildings in Azores. The in-plane behaviour characterization of this type of structural elements was also performed, as also the compression capacity of the masonry walls. The tests setups will be described along the manuscript as also the advantages, problems, limitations and improvement perspectives associated with testing schemes layouts.

Keywords: Experimental testing, stone masonry structures, infill masonry, out-of-plane loading, in-plane loading

1. Introduction

The use of experimental tests on structural engineering is widely used for the characterization of the expect behaviour and to characterize the structures properties, especially for the important outcome regarding the assessment and design objectives. Different types of tests can be performed on structures/elements such as material characterization tests, cyclic and/or monotonic behaviour characterization of structural elements or even the seismic performance assessment of complete structures. Each test should be defined taking into account the main goals and this choice depend significatively of technical and economic issues. Therefore it is possible to achieve equivalent experimental tests setups alternative to the preferable ones. The experimental testing of existing structures possesses great advantages but also some inconveniences, especially when dealing with masonry structures and with full scale specimens.

For instance, the simulation of the existing masonry materials under laboratorial conditions and the reproduction of the expect loads and also the representativeness of the local boundary conditions are one of the factors that increase the difficulties of this type of experimental characterization. On the other hand, a controlled environment under lab tests turns out possible the use of reaction structures and extensive instrumentation, characterizing more clearly the desire behaviour and taking into account any other possible disturbances to the test protocol.

The characterization of the out-of-plane behaviour of masonry structures suffer larger advances during the last years, through the implementation of different test approaches by several authors in the literature [1-5]. The main purpose of an experiment should be the reproduction of the real conditions that the specimen are subjected to. Concerning the earthquake evaluation of elements (e.g. walls, piers), the materials, axial load and boundary conditions are those parameters that should be more correctly controlled and conveyed to validate the experiment.

The present manuscript is related to the performance of out-of-plane tests performed with different approaches in stone masonry walls such in-situ or in laboratorial conditions. Point load tests and distributed loads were applied taking into account the complexity of the test setup and its applicability to laboratory or field conditions. *In-situ* experimental tests were performed in existing buildings, in Azores and additionally a large experimental campaign were carried out at the laboratory and the main findings related to the complexity and the advantages of each test approach will be described. With the experience acquired after the experimental campaign of out-of-plane tests of stone masonry walls it was developed at the Laboratory of Earthquake and Structural engineering (LESE) an innovative test out-of-plane test setup to evaluate the capacity of full-scale infill masonry walls. Furthermore, the in-plane behaviour characterization of this type of structural elements was also performed and information regarding the test setup will be described along the manuscript.

2. Experimental testing on stone masonry walls – *in-situ* and laboratory out-of-plane tests

2.1 *In-situ* experimental test in Azores Island

2.1.1 Point load out-of-plane test

Traditional building constructions of Azores, as in the Faial Island, mainly consist of masonry bearing walls giving support to wooden floor and roof structures. The most typical type is based on basalt or volcanic stone masonry, with dry joints or poor mortar layers between stones, although concrete block masonry is presently very spread throughout the building stock. Concerning the later, the most common situation is based on reinforced concrete frames filled with block masonry panels but, more recently (particularly after the last earthquake on July 1998), an increasing trend is observed to make this type of construction with duly confined concrete block masonry. In Fig. 1 are illustrated the stone masonry façade walls of two houses that were effectively tested within an experimental campaign.

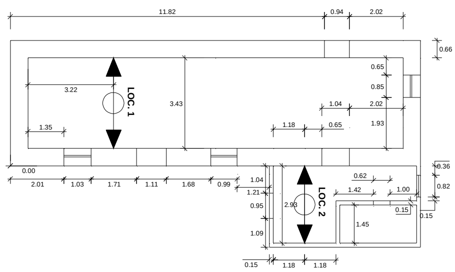
a)

b)

Fig. 1 - Effectively tested masonry types: a) two-leaf irregular masonry with poor fill material; b) two-leaf regular masonry with dry joints.

The basic idea of the adopted experimental system relies on simultaneous testing two opposite walls of a given house, by applying horizontal forces one against the other and resorting to a pair of hydraulic actuators operating under displacement control. Loading has been applied at the top of walls in the form of quasi-static increasing forces during repeated and alternate cycles, in order to simulate the horizontal action of roofs on masonry walls. Fig. 2a provides an overall view of the experimental set-up in one tested house, where two experiments were performed on the locations indicated in the plan layout shown in Fig. 2b.

a)

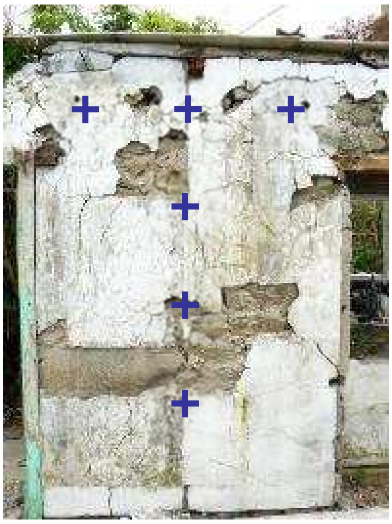


b)

Fig. 2 - Basics of the testing layout in house 1: a) general inside view; b) plan layout and test locations.

For each test the load was applied centred in a given wall panel between door/window openings and distributed along its length resorting to steel and wood pieces. Actuators were powered by a portable hydraulic rig and the whole system allowed applying forces up to about 120kN and maximum stroke +/-250mm. Displacements were measured by means of draw-wire transducers attached to external reference structures and actuator control could be done in terms of any of the transducers, depending on the particular features of each test.

Measurement points were always chosen according to a T-configuration in the plan of the tested wall as shown in Fig. 3a; this allowed obtaining the vertical deflected shape of the wall panel as well as any torsion movement that could occur at the top level due to different boundary conditions in the left and right sides. This measurement configuration was adopted for both opposite walls involved in the test which provided force-displacement information concerning two different walls for each test. As shown in Fig. 3b, the force was measured resorting to a load cell inserted in the loading system where appropriate hinged bearings have been include to avoid any bending moments.



a)

b)

Fig. 3 - Measurement details: a) layout of displacement measurement; b) load cell.

It is worth mentioning that with this testing system involving a pair of walls, a priori it is not known which wall will perform as the reaction wall because both can move. This is not a drawback of the system and, indeed, by taking adequate care with the actuator control, it is an advantage since two walls are actually being tested. Obviously, when the weaker walls starts degrading or failing, the other is no further explored in terms of imposed displacement, but in the general the obtained outcome consists of good information on the hysteretic behaviour of one wall up to failure and on the initial incipient cracking phase of the other wall.

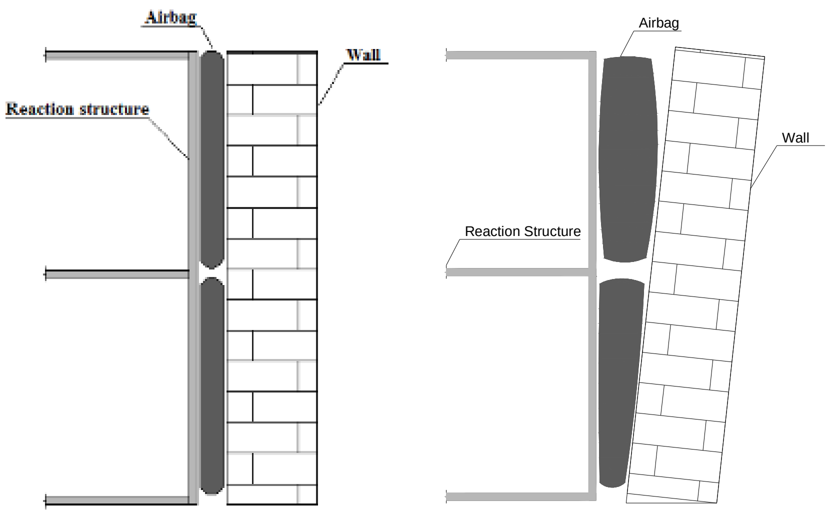
2.1.2 Distributed load out-of-plane tests

Taking into account the difficulties inherent to in situ tests, three fundamental orientation lines were defined: (i) the test setup should be self-equilibrated; (ii) high level of load capacity to perform experiments on strengthened specimens; (iii) ability to perform out-of-plane tests. Concerning its versatility and straightforward implementation, the testing system was designed to work with simple and light components (less than 30 kg), avoiding exterior reaction elements (self-equilibrated system).

The reaction frame defined for the experimental test was composed by tubular steel elements (ϕ=60 mm) connecting this reaction frame of the airbags to a reaction wall (part of the existing construction). Besides the metallic elements, there are two reaction surfaces to the airbags, constituted by wood elements and marine plywood plates (see Fig. 4).

Fig. 4 - *In situ* implementation for tests

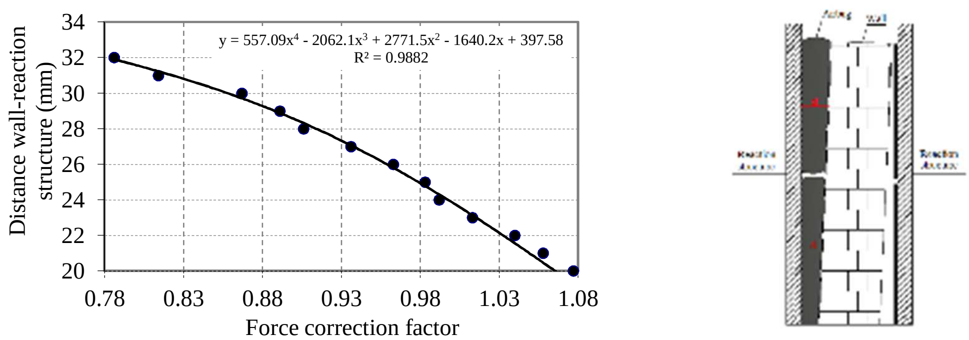
The test setup developed makes use of three airbags on each sides of the wall, one compressor, a series of pipes (ϕ=8 mm and ϕ=14 mm) connecting the airbags, pressure-control valves, displacement and pressure transducers properly connected to a portable data acquisition system. As already noted, the application of the distributed loads on this kind of test is not new have already been used in the past by other authors. However, the way how the test setup was implemented in experimental campaign, associated with an original structural configuration of the reaction system which allows bigger displacements, could constitute a step forward in this kind of tests, as well as its cyclic loads capability. The displacement of the wall relatively to the reaction structure is a key factor to estimating values of force during the airbag test. During the test, with the gradual inflating of the airbag, this displacement is responsible for the reduction of the contact area between the wall and the airbag. This phenomenon occurs because the inflated airbag does not assume a perfect rectangular parallelepiped shape presenting curved faces, leading to deficient contact areas near the boundaries of the airbag body (see Fig 5).



Underformed Deformed

Fig. 5 - Variation of the contact area for extreme displacement situations

In order to calibrate the contact area between the airbag and the wall, a laboratory full-scale test was performed, through which was possible to estimate a correction factor. Therefore, for a certain value of displacement, the correction factor is given by the ratio between the value measured by a load cell and the value measured by the pressure cell. In this test, the calibration was performed only for a single airbag. For the cases of tests with multiple airbags (see Fig. 6) the calibration process follows exactly the same procedure, resulting in a correction factor for each single airbag. In this case the control displacement (d) is determined in relation to the centre of gravity of each airbag.



Correction factor Control displacement, *d*

Fig. 6: Correction model of the contact area.

2.2 Laboratory experimental tests

As already introduced, this experimental campaign aimed at characterizing the out-of-plane behaviour of full-scale masonry walls resorting to quasi-static loads applied by means of two different testing setups and under three distinct pre-compression states. The first test setup consisted of the application of a uniformly distributed surface load using a system of three nylon airbags (with 1600 mm height, 700 mm width and 350 mm thick), which reacts against a backing frame. The latter is connected to a reaction structure composed of a set of HEB steel beams, connected to the reaction wall of the laboratory with mechanical anchors (Fig. 7). The level of pressure inside the airbags and the top displacement of the specimen, used as control displacement during the tests, were continuously acquired through a data acquisition system.

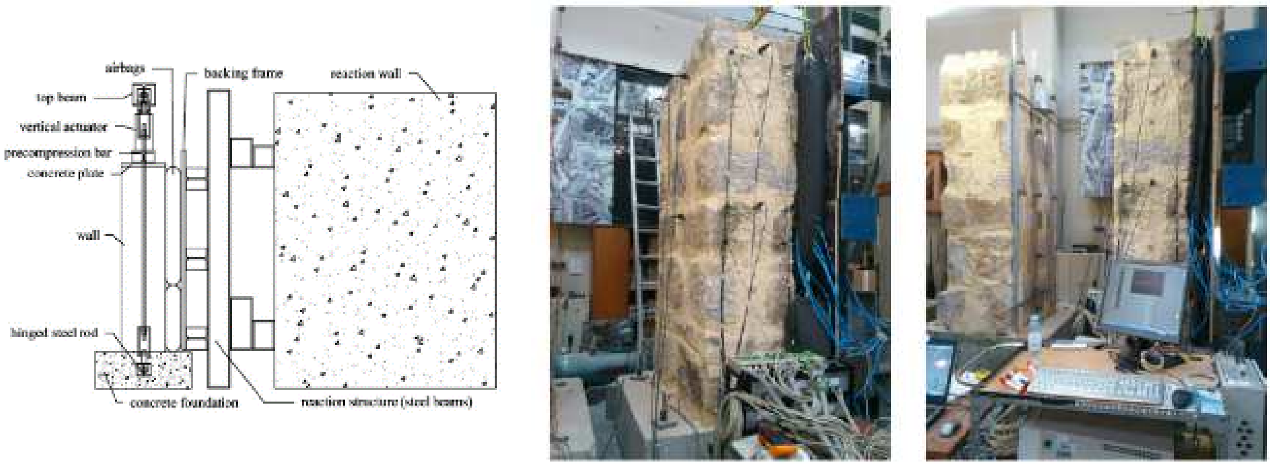


Fig. 7: Out-of-plane distributed loads using airbags test setup implemented in the Laboratory of Earthquake and Structural Engineering.

The second test setup consisted on the application of a horizontal line-load by means of a displacement-controlled hydraulic actuator. In order to avoid an eventual torsional response of the specimen, the actuator was horizontally centered at the top of the back surface of the masonry wall. The actuator reaction is provided by a stiff steel structure, anchored to the test slab of the laboratory, Fig. 8. Concerning the foundations of the specimens, it is worth mentioning that these traditional masonry constructions usually do not include any special foundation element, being simply settled on soil with some layered bottom stones right below the ground level. This situation is naturally more common in low-rise buildings, which usually do not need very deep and large foundations. Consequently, aiming at full control the boundary condition of the experiments, all the masonry walls were tested on a cantilever structural scheme, settled on a concrete footing, independently from the pre-compression level and the test setup. Note that, even in the most unfavorable case, i.e. with no axial compression force, the friction between the concrete footing and the first layer of granitic stones is sufficient to guaranty that no sliding will occur at the base of the wall. This issue was also monitored during the experiments with a displacement transducer between the bottom of the wall and the concrete footing, and no sliding occurred. In order to apply the vertical load, a hydraulic actuator was installed at the top of the masonry wall, reacting against a steel frame connected to the foundation through hinged steel rods in which load cells were used to measure the imposed force. As the vertical hydraulic actuator used is not force-controlled and consequently a significant variation of vertical compression was observed during the experimental tests. This non-negligible load variation was due to the absence of oil volume correction inside the hydraulic actuator to compensate the uplifting and the vertical deformation of the specimen.

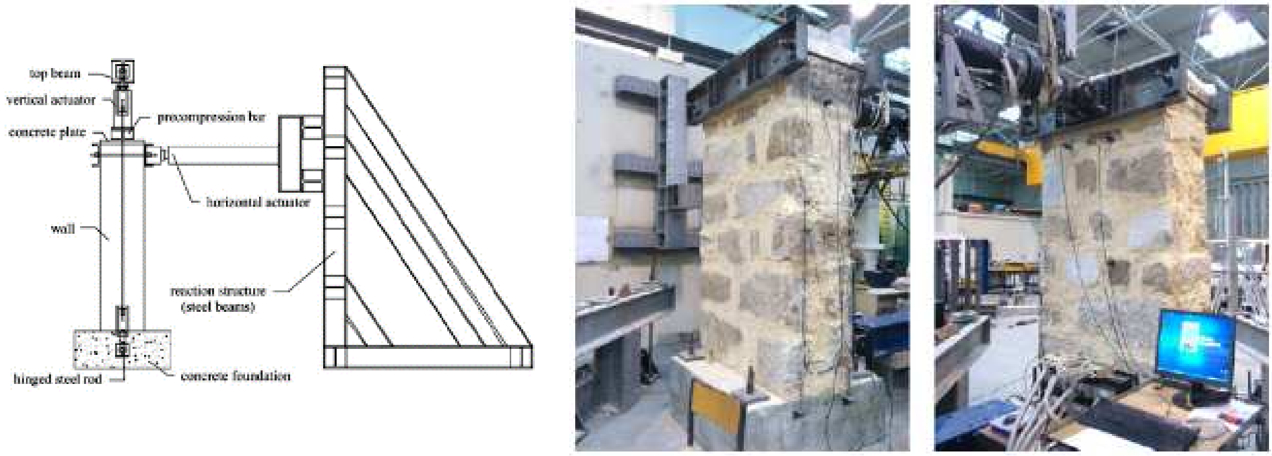


Fig. 8: Out-of-plane point load test setup implemented in the Laboratory of Earthquake and Structural Engineering.

3. Experimental testing of full-scale infill masonry walls – in-plane and out-of-plane laboratory tests

It is consensual that further and deeper knowledge is required of the out-of-plane behaviour of infill masonry (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 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, different types of masonry bricks, etc. 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 [6-9]. It was observed that the out-of-plane capacity of the IM walls is reduced with the increase of the 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 this type of experimental tests some important considerations can be withdrawn for the future, and in particular can be fundamental to earthquake prone countries, namely:

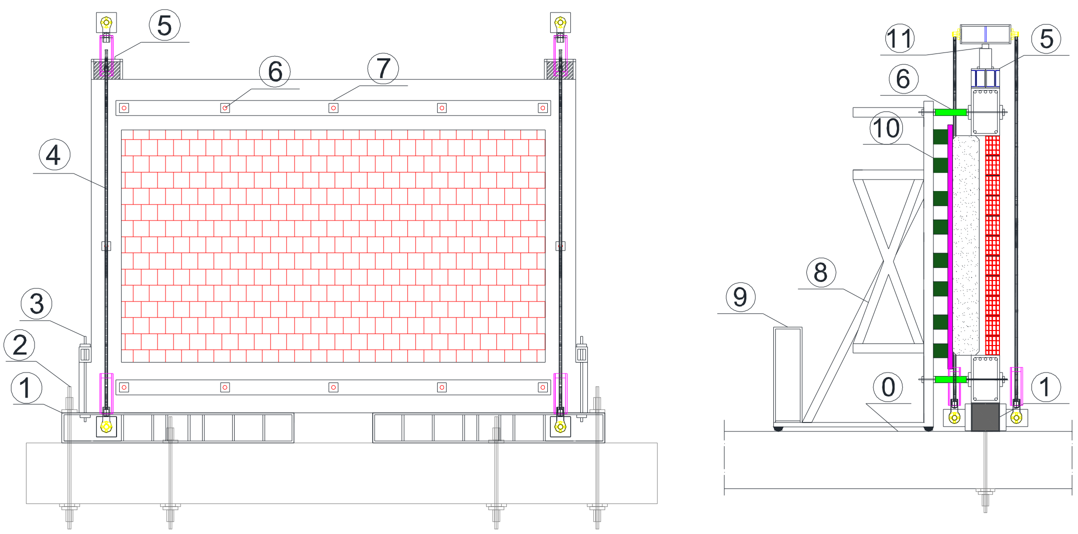
- The structural designers are sensitized to take into account with the structural contribution of this non-structural elements in the buildings response when subjected to earthquake loadings;
- With the experimental characterization of the IM walls it is possible to develop some strengthening strategies 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;
- 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.);
- 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 and with the knowledge acquire from the experimental campaign of the out-of-plane tests performed in full-scale stone masonry walls, an innovative test setup was developed to characterize the out-of-plane behaviour of IM walls with geometry based on a previous statistical study conducted into Portuguese RC building stock, namely buildings constructed in the 1960's and 70's [10]. Additionally an in-plane test setup was developed to characterize the capacity of infilled RC frames under loadings along their plane. Further information regarding both tests setup will be described along the next sub-sections.

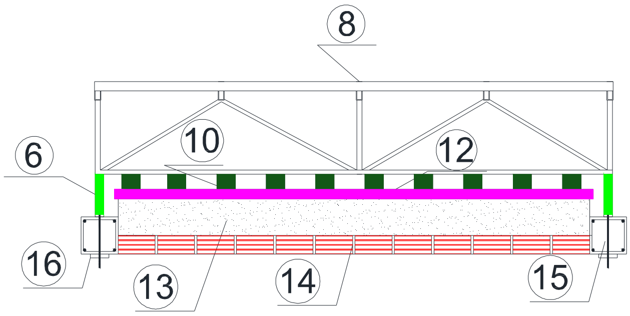
3.1 IM walls out-of-plane test setup

The out-of-plane test consisted of the application of a uniformly distributed surface load through a system composed of seven nylon airbags, reacting against a self-equilibrated steel structure, as shown in Fig. 9 and Fig. 10. 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, as verified in the previous section. This reaction structure is composed of five vertical 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 [11]. 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)

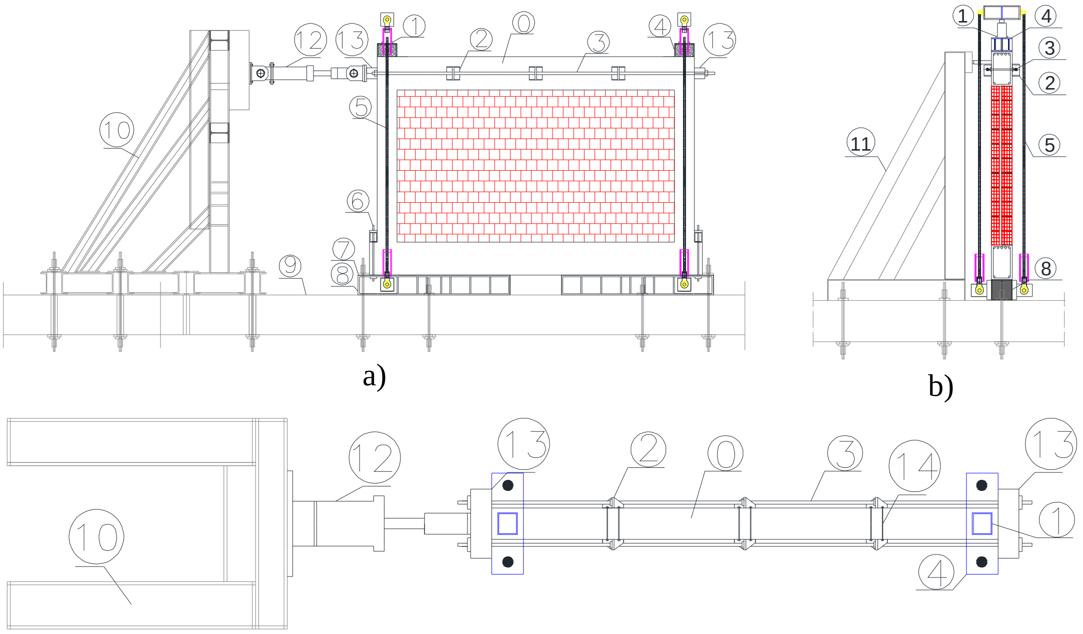
Fig. 9 – Layout of the out-of-plane test set-up: a) front, b) lateral and c) plan view. 0 – strong floor, 1 – foundation steel shape, 2 – high-strength rods (ø30mm) fixing the foundation steel shape to the reaction slab, 3 – steel rod (ø20mm) connecting the RC frame to the foundation steel shape, 4 – vertical high-strength rods (ø30mm) to apply axial load, 5 – steel cap, 6 – steel rods (ø20mm) connecting the RC frame and the reaction structure, 7 – distributing load plate, 8 – self-equilibrated reaction steel structure, 9 – counterweight, 10 – wood bars, 11 – hydraulic jack (for axial load application), 12 – vertical wooden platform, 13 – airbags, 14 – infill panel, 15 – RC column, 16 – steel plate for rod force distribution.

a) b)

Fig. 10 – General view of the out-of-plane experimental test set-up: a) front view, b) lateral view.

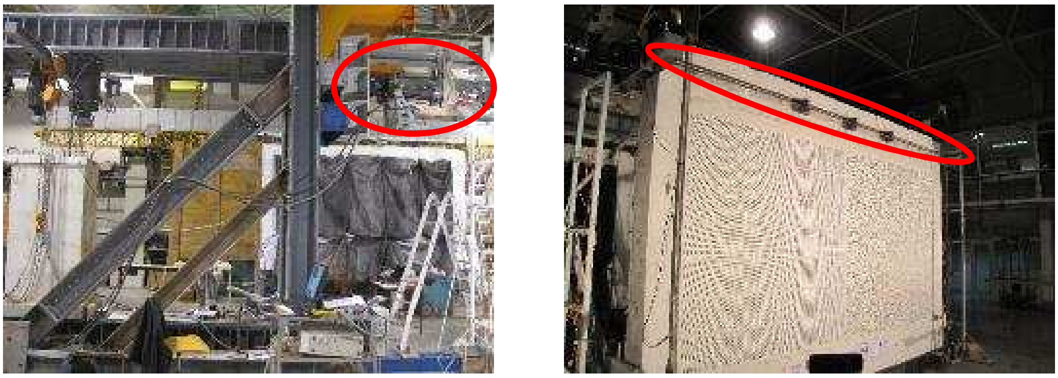
3.2 IM walls In-plane test setup

The in-plane test consisted of the application of a horizontal force on the top of the RC frame using a servo-controlled hydraulic actuator (+/-500kN capacity with +/-150mm stroke) attached to a steel reaction structure (Figure 11). The horizontal force was transmitted to the RC frame by two high strength rods (ø22mm) (in the front and rear specimen sides) tying two steel shapes at the left and right extremities of the top beam (Figure 12), in order to apply in-plane loading cycle reversals. The two high strength rods were linked at 1/4, 1/2 and 3/4 of the beam length to steel plates that connect with the corresponding one of the other side of the beam by 2 steel rods (ø10mm) with the main objective of mobilize and distribute the in-plane load along the entire top beam cross-section uniformly. The column axial load was applied using one hydraulic jack per column, attached to the top and bottom of the steel devices by means of high-strength rods with hinged extremities. The in-plane infilled frame was tested under the so-applied column axial load of 300kN kept constant with the prescribed value measured by load cells attached to the jacks. The test set-up was also provided with an additional guiding structure to prevent out-of-plane displacements of the infilled RC frame, while allowing it to slide along the steel shape guides. Fig. 11 shows the layout of the in-plane experimental test set-up, illustrating each element with a corresponding description.



a) b) c)

Fig. 11 – Layout of the in-plane experimental test set-up: a) Front view; b) Lateral view and c) Back view. 0 – Top beam, 1 – hydraulic jack (for axial load application), 2 – steel plates for horizontal force distribution, 3 – horizontal high-strength rods (ø22mm), 4 – head steel shape, 5 – vertical high-strength rods (ø30mm), 6 – steel rod (ø20mm) connecting the RC frame to the foundation steel shape, 7 – high-strength rods (ø30mm) fixing the foundation steel shape to the reaction slab, 8 – foundation steel shape, 9 – strong floor, 10 – in-plane reaction frame, 11 – out-of-plane reaction and guiding structure, 12 - Servo-controlled hydraulic actuator, 13 – Right and left head steel profile and 14 - 5 – Transversal rods (ø12mm).



a) b)

Fig. 12 – Detail of: a) Servo-controlled hydraulic actuator (+/-500kN capacity with +/-150mm stroke) attached to a reaction steel frame; and b) horizontal high-strength rods (ø30mm) that are connected to the left and right steel profile placed at mid-height of the top beam.

5. Conclusions

This work included a general overview of different topics, starting with the experimental out-of-plane behaviour characterization of unreinforced and strengthened stone masonry walls, namely through the presentation of an *in situ* experimental campaign carried out on typical masonry constructions of Faial Island, Azores. The outcome of such tests is of utmost importance for understanding the behaviour of traditional masonry walls as they exist, particularly concerning the out-of-plane response as addressed in this study. Experimental tests developed in full-scale stone masonry walls in laboratory were also presented and the main findings related to the complexity and the advantages of each test approach were also discussed. The outcome of such tests is of utmost importance for understanding the behaviour of traditional masonry walls as they exist, particularly concerning the out-of-plane response as addressed in this study. A significant contribution is also achieved for appropriate numerical modelling calibration.

Finally, it was presented an innovative test setup developed at the Laboratory of Earthquake and Structural Engineering (LESE) to perform static out-of-plane tests of full-scale IM walls with and without previous in-plane damaged with the main goal of characterize the interaction between the in-plane and out-of-plane capacity and develop efficient strengthening solutions to improve this non-structural elements seismic performance

Acknowledgements

The authors would like acknowledge to the Laboratory of Earthquake and Structural Engineering (LESE) Mr. Valdemar Luis and Mr. Nuno Pinto for all the support in the preparation of the experimental tests.

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