RESEARCH PAPER

Perspectives and Approaches for the Out-of-Plane Testing of Masonry Infill Walls

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Abstract

It is widely accepted that further and more in-depth research is required on the out-of-plane seismic response of masonry infill walls to increase knowledge regarding this particular behaviour and to develop effective strengthening strategies for preventing their collapse. However, such experimental tests are difficult to perform and the scientific community recognizes the complexity inherent to the test apparatus, loading approaches and loading protocols. At the Laboratory for Earthquake and Structural Engineering (LESE), several efforts were carried out over the last years towards characterizing the out-of-plane behaviour of full-scale MIW. Two test setups were developed using two different approaches for applying the out-of-plane loadings. This manuscript provides an overview of the test setups adopted in the literature by other authors and discusses their implication in the MIW response. Therefore, the considerations assumed in the development of the test setups at the LESE laboratory are provided starting by describing the out-of-plane tests with airbags and after that with pneumatic jacks. Further information regarding both tests setups is described and discussed throughout the manuscript. Experimental results of two specimens tested with both approaches are presented, highlighting the main differences and similarities.

Introduction

The use of experimental tests for structural engineering is widely popular for characterizing the expected behaviour of structures and/or structural elements and their mechanical and material properties, to obtain required information for the safety assessment of existing structures and/or design of new structures. Different types of experimental tests can be performed with the same goal, namely quasi-static or dynamic tests where the specimen is subjected to quasi-static or dynamic loading to simulate the seismic demand. Each test is planned according to prescribed goals, and their choice depends on technical and economic issues and the capability of the facilities.

In recent years, the interest in studying the masonry infill wall (MIW) out-of-plane (OOP) behaviour increased significantly. A high number of OOP collapses was reported in numerous post-earthquake survey damage assessment reports [1–5]. Due to their interaction with the surrounding reinforced concrete (RC) frame, MIW can develop enhanced OOP strength through an arching mechanism, which mainly depends on slenderness, masonry compressive strength, boundary conditions and panel support width conditions. The MIW seismic vulnerability can increase due to constructive detailing aspects that, nowadays, are commonly adopted throughout the Southern European countries. For example, the following issues can contribute to the reduction of the panels OOP strength and deformation capacity and thus increase their risk of collapse, namely: i) no connection between the panel and the surrounding RC elements; ii) no connection between the internal and external leaves (in the case of double-leaf infill walls) and, iii) reduced width of the panel support. In this framework, experimental studies are essential to understand the OOP behaviour of the infill panels, especially for OOP failure combined with prior in-plane (IP) damages, and numerical models are fundamental to study their effect in the global building behaviour.

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The investigation of this issue deepened in the 1990s [6], from which it was concluded that the OOP strength reduces with the panel slenderness. Some authors also observed that the panel aspect ratio could have a substantial effect on the OOP behaviour [7]. The IP-OOP behaviour interaction seems to be one of the most critical issues since different authors report that the previous damage reduces the panel OOP strength [8]. The boundary conditions also affect the panel OOP behaviour, since it modifies the failure mechanism and their OOP strength [9]. The role of the manufacture quality is pointed out again as a factor that could introduce variability regarding the panel OOP behaviour response [10]. However, accounting for the lack of experimental studies carried out over the last years regarding the OOP behaviour of infill walls and considering, in particular, the common use of hollow clay horizontal bricks in many European Countries, in the last decades, it is of utmost importance to evaluate the seismic performance and to propose strengthening strategies.

Different types of approaches are being adopted to perform the out-of-plane tests, such as scaled or full-scale specimens. Other loading protocols are assumed since there is a lack of specific standardization and international recommendations.

This manuscript aims first to provide an overview and perspective of the actual panorama of the out-of-plane testing of MIW. Details of the test setups available in the literature are provided and discussed. The loading protocols and approaches assumed by the authors are presented. The second goal is to explain the development process of the test setup using airbags and pneumatic jacks in the Laboratory for Earthquake and Structural Engineering. For this, examples of tests of full-scale MIW are provided, illustrating the potentiality and limitations of each setup. Finally, future works and challenges are drawn.

Literature Overview of the Out-of-Plane Testing of Masonry Infill Walls

Over the literature, there are a small number of testing campaigns related to the study and characterization of the MIW OOP behaviour of steel or RC frames [11–23]. Part of these studies consisted of shaking table tests of single infill panels or scaled infilled RC structures [24–31]. A literature search shows that a few types of tests were conducted to study the MIW OOP behaviour, namely: quasi-static tests (monotonic or cyclic), pseudo-dynamic tests and shake-table tests. A recent systematic review points out that 67% of them are composed of monotonic tests, 23% cyclic tests and, finally, 9% shake-table tests [32]. Concerning the specimens' scale, 66% were full-scale tests while the remaining are related to scaled models, namely 1:1.5, 1:2, 1:3 and 2:3. Most of the tests were carried out in as-built infill walls (76%), the remaining ones
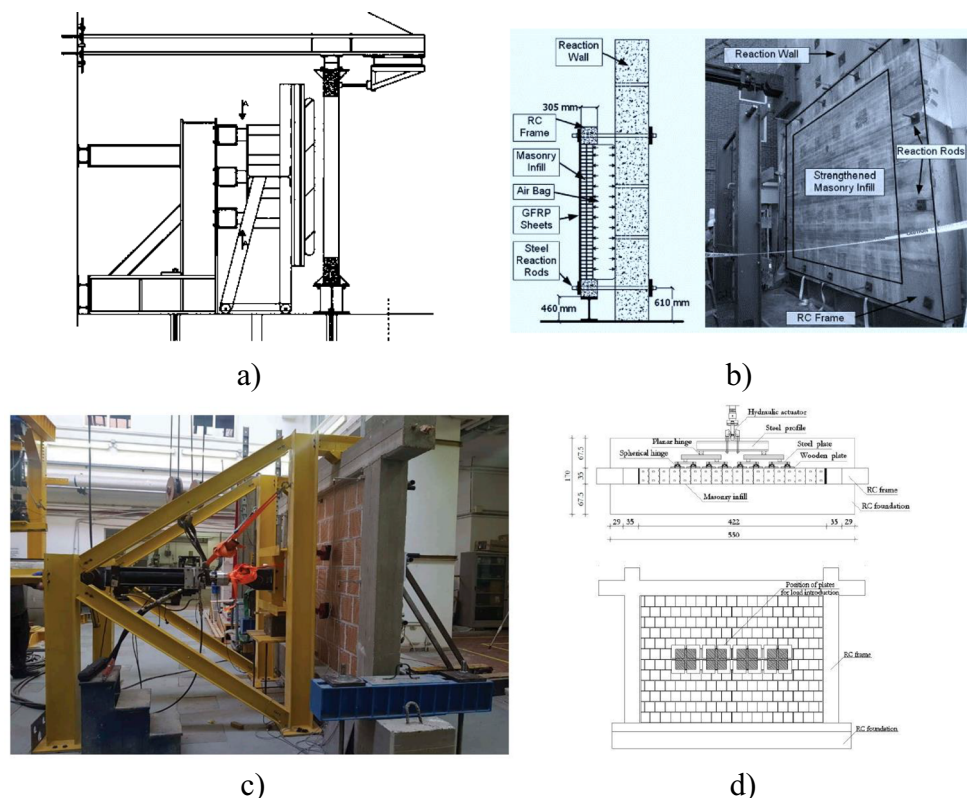

Fig. 1 – Loading application approaches: (**a**) Airbag (adapted from Silva [38]; (**b**) Airbag with the RC frame structure attached to a reaction wall (adapted from Lunn and Rizkalla [39]; (**c**) 4 points load application not aligned (adapted from [9]; (**d**) 4 points load application aligned (adapted from Hak, et al. [19])

were on retrofitted panels (19%) and panels with bed joints' reinforcement (6%). It was observed that an envelope frame made of RC instead of steel surrounded most of the panels tested.

Regarding the quasi-static tests, the studies considered different loading protocols. A 3D motion characterizes an earthquake, which means that the panel is subject to combined and multiple loadings, such as IP-OOP horizontal loadings combined with gravity loads (applied by the top structural frame members). The laboratory reproduction of these combined multiple-directions is challenging to simulate due to the test setup complexity. From the tests available in the literature, most of them (49%) are related to pure OOP tests. Concerning 15% of them, which are related to combined IP-OOP tests, the loading protocol was divided in two independent stages, namely: i) first, an IP test was performed to impose some certain level of damage to the panel; ii) second, a pure OOP loading was applied on the damaged infill panel.

Fig. 2 – Layout of the OOP test set-up: (**a**) front, (**b**) plan, (**c**) detail of the load cell and (**d**) lateral view
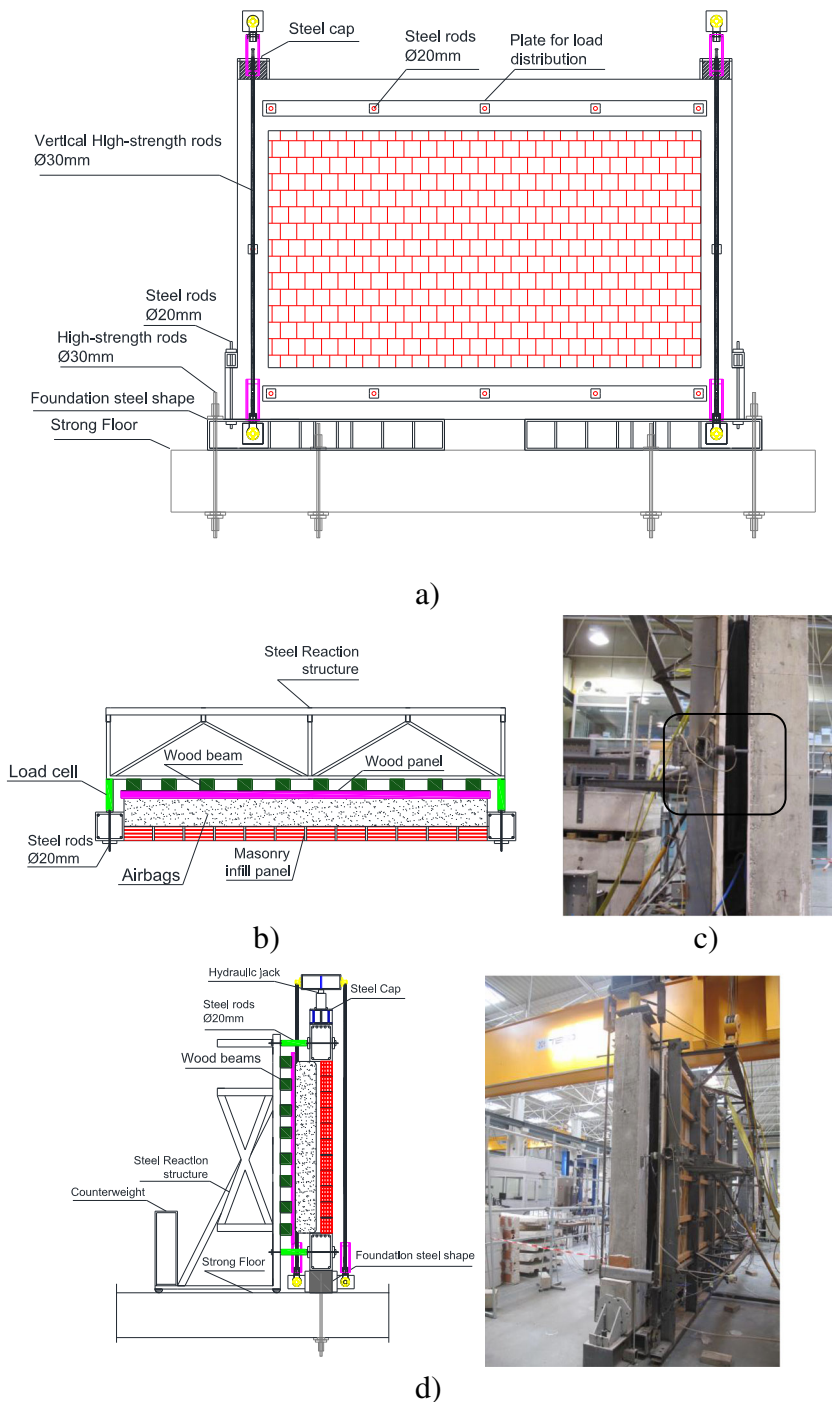
Fig. 3 – General view of the OOP experimental test set-up: (**a**) front view, (**b**) near view

a)

b)

These tests are essential to understand the effect of the damage, due to previous IP loading demands, in the infill panel OOP capacity. The IP-OOP tests combined with the application of gravity load totalize 22% of the tests. For this type of loading protocol, different strategies were assumed for the application of the gravity load application namely: i) some authors applied it directly in the top of the upper beam; ii) while some others applied it in the top of the adjacent columns. The correct strategy to apply the gravity load has not been agreed upon, due to uncertainties associated with the loading distribution, which can be transferred to the wall and/or to the columns.

Moreover, the high level of complexity of the test setup required applying the axial load and the strategy to apply the horizontal load, as already mentioned, is a significant limitation. In a real scenario, the MIW is subjected to specific gravity load (infill panel vertical load), imposed by the short and long-term deformation of the top beam/slab. Due to this, most of the experimental tests were carried out without application of any additional vertical load. Concerning the effect of the gravity load applied in the MIW, it is reported that it affects the response mechanism, since it increases the confinement of

the panel. When it occurs the sliding of the panel from the adjacent beams it could lead to higher energy dissipation. It is reported in the literature that the trilinear cracking observed without an axial load applied in the adjacent columns changed to pure vertical crack [33].

Different strategies were adopted to apply of OOP load, from uniform distributed loadings throughout the entire panel to local loads specifically distributed. This concept was first tested and validated by Mosallam [34] that used water bags to apply a uniform distributed OOP loading in red bricks walls strengthened with fibre reinforced polymer (FRP) composites. In the same year, Griffith, et al. [35] tested the same concept but used airbags to apply uniform OOP loading to stone masonry walls. Griffith, et al. [35] carried out tests using double-actuation airbag' system, one in each face of the specimen that enabled OOP cyclic loading instead of the load-unload inherent to the using only one actuation airbag system. One of the disadvantages related to the use of double-actuation airbag system is the impossibility of observation of the damage evolution throughout the test. Apart from that, the synchronization between the two-airbag actuation components is also considered a difficulty. The use of local loads at four or eight points applied by hydraulic actuators is commonly adopted to overcome the difficulties due to the complexity of test setups that ensure the entire mobilization of the panel. However, one disadvantage concerning this approach is the possibility of introducing of a local failure or modifying the global MIW behaviour when compared with the expected one during a real earthquake. From the analysis of all the testing campaigns, different loading protocols were adopted regarding the definition of the number of half-cycles per peak displacements, the definition of the OOP peak displacements applied and finally, concerning the definition of the ultimate displacement.

The use of airbags revealed to be very effective for the realization of the OOP tests, as proved by the recent works developed in the masonry field [35–37]. As can be observed in b, about ninety OOP tests were carried out within the application of the OOP loading with airbags. Silva [38] carried out
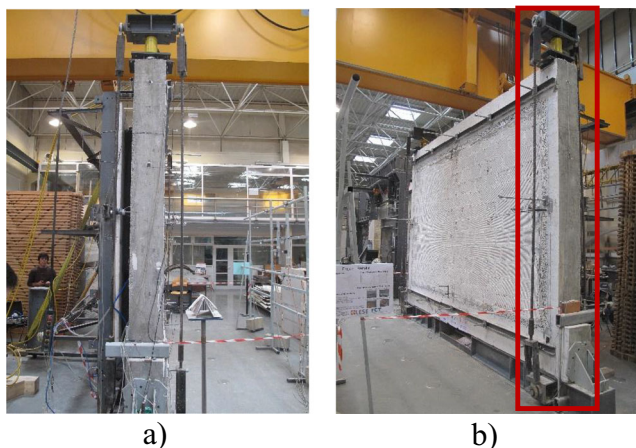

a)

b)

Fig. 4 - Test setup view: axial load application in the top of the RC frame columns (**a**) profile view; and (**b**) lateral view

OOP quasi-static tests by using airbags that reacted against an independent steel reaction frame (Fig. 1(a)). The authors also restricted the OOP displacements of the envelope frame by using steel braces that were connected to the top beam. Alternatively, Lunn and Rizkalla [39] performed OOP quasi-static tests using airbags that were placed between the panel and a RC shear wall. This wall was attached to the envelope RC frame in 14 points (5 connections in the top beam, five connections in the bottom beam and 2 in each column) using steel rebars (Fig. 1(b)). Di Domenico, et al. [9] assumed a different approach where the OOP loading was applied in 4 points not aligned using a hydraulic actuator reacting against a steel structure and dividing the OOP load into 4 points (Fig. 1(c)). Finally, Hak, et al. [19] performed full-scale OOP quasi-static tests using a hydraulic actuator that was also reacting against a steel structure and distributing the OOP loading into four aligned points (Fig. 1(d)).

Development and Validation of an OOP Testing Setup for Full-Scale Masonry Infill Walls Using Airbags

Introduction

This section aims to describe the development of the test setup developed for OOP testing of full-scale MIW using airbags. This section starts with a summary of the concept behind the definition of the teste setup. This discussion will highlight some of the significant concerns and limitations in the report of this setup. In parallel, the advantages and disadvantages of this test setup are presented. After that, the test setup is deeply presented and explained, focusing the innovative concept of a self-equilibrated reaction structure for OOP testing of MIW. The loading control system is briefly introduced to provide full understanding behind the operation of the overall design. Finally, it is given the example of an experimental test carried out using this concept, in which a non-strengthened MIW, without plaster, made with hollow clay horizontal bricks is tested. The results are analysed and discussed, and validation of the results by other authors are presented.

Concept, Vantages and Disadvantages

One of the primary goals of the MIW OOP testing is to reproduce correctly the seismic forces that usually occurred during an earthquake. Due to the distributed MIW mass configuration, the test setup herein presented was designed to mobilize the entire panel through the application of a distributed loading. Different approaches have been proposed in the literature, as above described.

From the characterization of the expected MIW OOP seismic response, through quasi-static cyclic tests, the use of airbags reveals is very interesting since it applies OOP loadings with similar shaping to the MIW first OOP vibration mode [40]. In this type of test, the OOP loading control is

Fig. 5 - Control system: (**a**) Schematic layout of the airbag loading system; and (**b**) Control system diagram of OOP cyclic tests
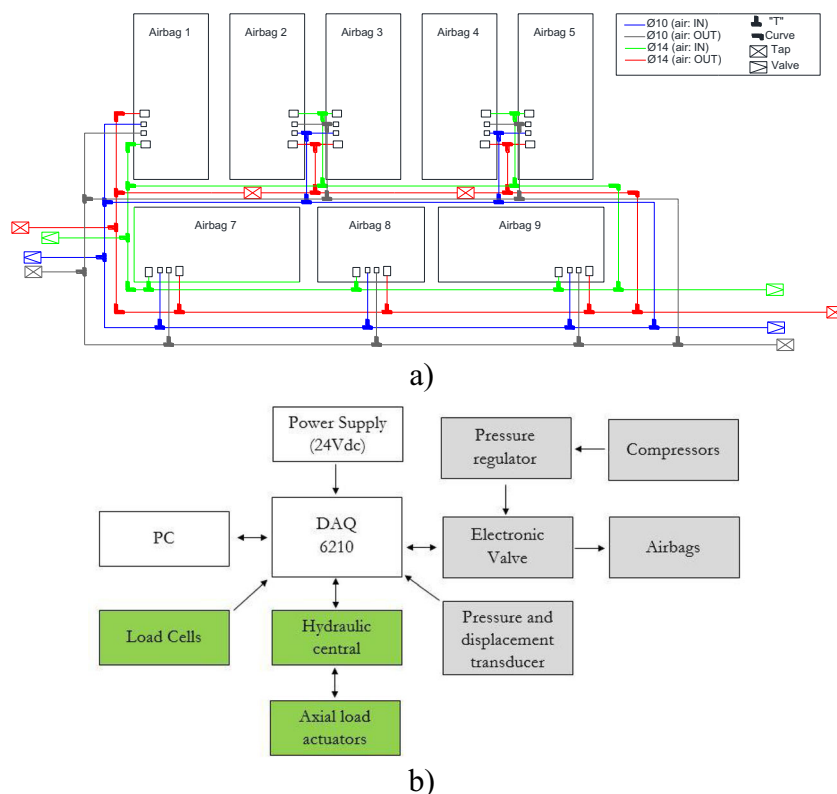
carried out by pressure cells that have direct interaction with a specific displacement transducer (displacement control testing), which means that target displacements are defined for a particular point of the MIW before the test. The pressure cells allows the air entrance to the airbags and the OOP load applied in the surface of the panel increases. When the panel reaches the target displacement, the pressure cells turns out the air inside of the airbags.

The major disadvantage of this test setup is common to all of those carry out with airbags, namely the limitation of the MIW geometric dimensions according to the airbags dispositions and dimensions. The mandatory need for adopting a new configuration of the airbags if there is a modification of the MIW geometries or inclusion of openings is one of the limitations. Another limitation, inherent to the OOP testing using airbags is the impossibility of observing the damages from the backside of the MIW during the test. There is a need for placing the instrumentation in front of the panel. This fact restricts the realization of the OOP tests until reaching the MIW collapse.
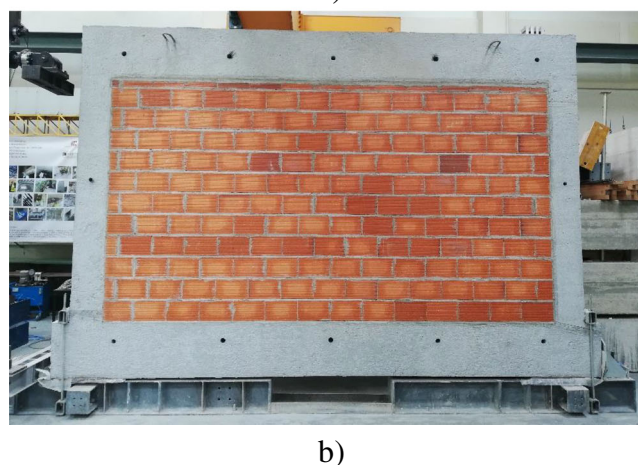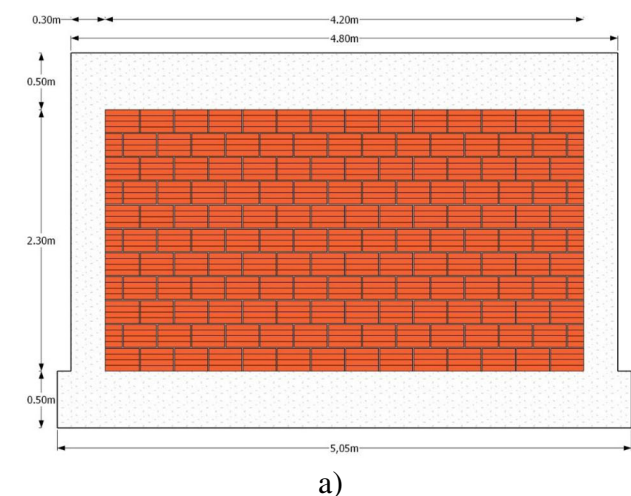

a)

b)

Fig. 6 – Infilled RC frame specimen dimensions (units in meters): (**a**) general dimensions and (**b**) front view of the specimen

Test Setup Description

As mentioned in 3.1, a new test setup was designed at the Laboratory for Earthquake and Structural Engineering, comprising a self-equilibrated steel structure, which is connected to the RC frame structure that provides support to the airbags that are placed between the MIW and the steel reaction structure. This setup is complemented with the possibility of applying different axial loads on the top of the adjacent RC columns. The major innovation of this test setup is related to the fact that the reaction of the OOP pressure that is applied over the MIW surface is provided thanks to the bare frame strength and stiffness. This self-equilibrated concept allows the performance of OOP tests without the need for a robust external reaction structure, which is usually associated with strong structural elements (shear walls or strong slabs).

This test consists of the application of a uniformly distributed surface load through a system composed of seven nylon airbags, reacting against the self-equilibrated steel structure, as shown in Figs. 2 and 3. 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, are used to equilibrate the reaction force resulting from the pressure applied by the airbags in the infill panel. The steel rods are 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 (Fig. 2(c)). On the other extremity of each tensioned rod, proper nuts and steel plates are used to anchor the rod. It is also used to 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.

This test setup has the possibility of applying vertical axial load in the top of the frame columns. The axial load is applied in each column using a hydraulic jack inserted between a steel cap placed on the top of the column and an upper HEB steel shape. This steel shape is 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 applied to the columns is continuously measured by load cells inserted between the jacks and the top of each column (Fig. 4).

The pressure level inside the airbags was set by two pressure valves, which are controlled according to the target displacement. The OOP displacement of the central point of the infill panel (the control node and variable) is continuously acquired during the tests using a data acquisition and control system developed in the National Instruments LabVIEW software platform [41].

Fig. 7 – Test result: (**a**) First macro-cracking; (**b**) cracking pattern (Front view); (**c**) detail of the deformation in the centre of the panel; (**d**) damages observed (near view); (**e**) Force-displacement response

a)

b)

c)

d)

e)
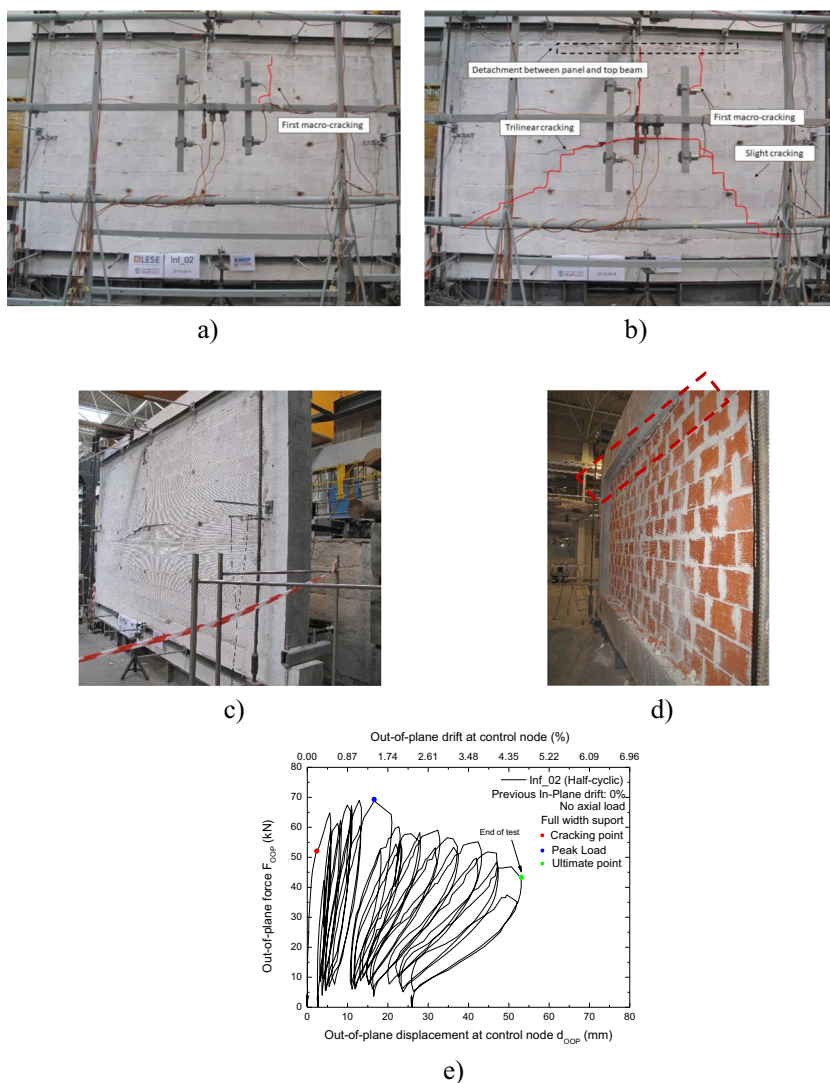
Testing Control System Overview

The control system is composed of two main components: (i) airbag control; and (ii) axial load control. The airbag control is formed by two electronic proportional directional control valves (0-10 bar), two air compressors (100lt, 10 bar), two manual filters pressure regulators (0-16 bar) and two transducers (pressure and displacement). Each air compressor is connected to one pressure regulator (limit defined as 2 bar) and one electronic valve, respectively, to guarantee two air entrances on the airbags set (one in each extremity). The panel loading is ensured by the airbags inflation control while monitoring their internal pressure and the imposed OOP displacements in the infill panel. The schematic layout of the airbag loading system is presented in Fig. 5.

The implemented airbag control program is displacement control based, where a specific displacement transducer is defined as the reference one, for which a target displacement history is described previously. The comparison between the target and the measured displacement and the interaction with the electronic pressure valves drive the control requirements of air inflation or deflation. The axial load application and control was carried out through a hydraulic central, two hydraulic jacks and two load cells (AEP) as described in the previous subsection.

Example of Application – As-Built Infill Wall without Opening

Specimen geometric dimensions and characteristics

The MIW specimen geometric dimensions are 4.20 × 2.30 m (length and width respectively, which is representative of those existing in the Portuguese building stock according to the study developed by [3], and shown in Fig. 6(a), (b). The columns and beams' cross-sections were considered as 0.30 × 0.30 m and
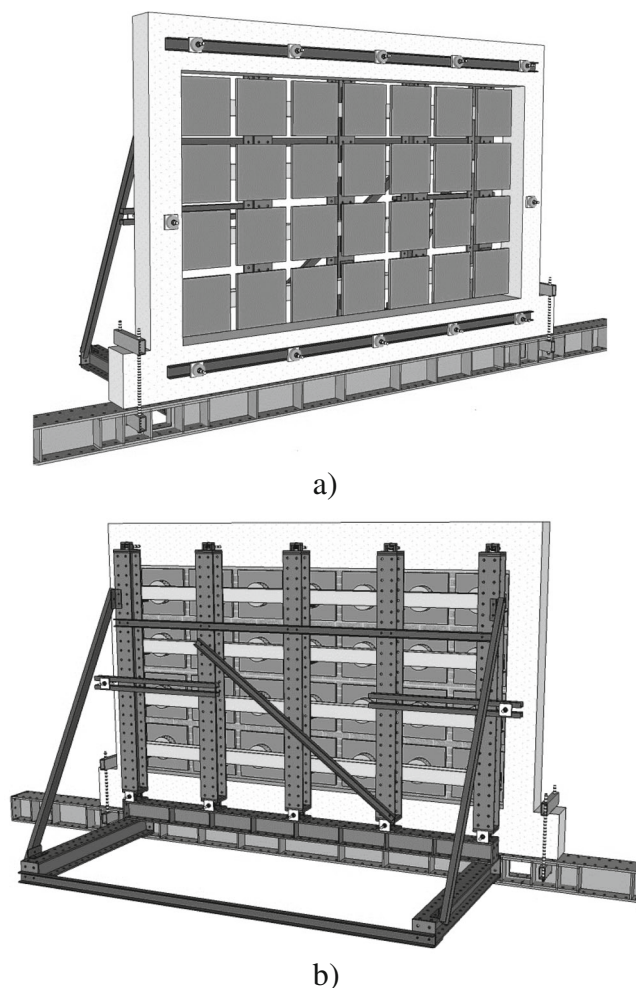
a)

b)

Fig. 8 – Layout of the OOP test set-up using pneumatic actuators: (**a**) front and (**b**) near view

0.30×0.50 m, respectively. No seismic design was considered for the frame detailing.

All the infill panels have equal geometry with the above-mentioned in-elevation dimensions, made of hollow clay horizontal brick units 150 mm thick. No reinforcement was used to connect the infill panel and the surrounding RC frame, and no gaps were adopted between the infill panel and the frame. The grades C20/25 and A500 were adopted for concrete and reinforcing steel, respectively. The specimen was built with all the panel width supported at the bottom beam, which implies that the external faces of the infill panel and outer front of the RC elements are in the same alignment plane. The mortar adopted was a typical ready-mix commercial M5 class type. No plaster was adopted.

Experimental result

The first crack observed for an OOP drift of 0.11% and a corresponding total force equal to 51.09kN, is shown in

Fig. 7(a). After that, a slight detachment of the MIW from the top beam triggered a trilinear crack, as shown in Fig. 7(b). The deformation of the MIW was all concentrated in the centre of the panel, as visible in Fig. 7(c). Figure 7(d) shows the back view of the infill panel, from which it occurred crushing of some bricks in the top of the infill wall due to the development of arching mechanism followed by the detachment from the top beam. The specimen Inf_02 achieved a maximum OOP strength of 6.94 kPa for an OOP drift of 1.44%. A residual strength equal to 37.80kN was reached for an OOP drift equal to 4.7%. The criteria to stop the test was the purpose of avoiding the MIW collapse, which could damage the instrumentation that was located in the panel front. The cracking pattern of the specimen is plotted in Fig. 7(b) and the force-displacement response in Fig. 7(e).

OOP Testing of Full-Scale Masonry Infill Walls Using Pneumatic Jacks

Concept, Vantages and Disadvantages

A novel test setup was developed, inspired in the setup above presented, based in the application of a distributed OOP loading through several pneumatic actuators that mobilize the entire MIW surface resorting to wood plates (one per actuator) placed between the actuators and the panel. One of the reasons behind this upgrade was the aim of providing more stiffness and robustness to the reaction structure to support stronger infill walls. Additionally, this new testing platform can test MIW with openings (with different configurations and dimensions) and was designed to allow performing combined IP-OOP quasi-static tests. This new test setup also allowed placing the instrumentation in the back of the reaction structure, which helps to perform OOP tests until the panel collapse without damaging any equipment. In addition, the identification of panels' cracking throughout the OOP tests becomes easier as also the quality of the pictures and films recording of each test improved significantly. Soon, it will be possible to apply different OOP loading patterns, alternatively to the traditional uniform shape.

Test Setup Description

This setup is based on the same concept of the previous one, namely the idea of a self-equilibrated system, which balances the transmission of the OOP loadings to the reaction frame that is attached to the RC frame. Thus, this new test setup uses pneumatic actuators that are linked to four horizontal alignments performed by HEB140 steel shapes, which react against five vertical alignments also made of HEB200 steel shapes. The horizontal alignments are coupled with hinged devices that allow lateral sliding. The steel structure is attached to

Fig. 9 – View of the OOP test set-up using pneumatic actuators: (**a**) overall view; (**b**) lateral view; (**c**) near view and d) front view
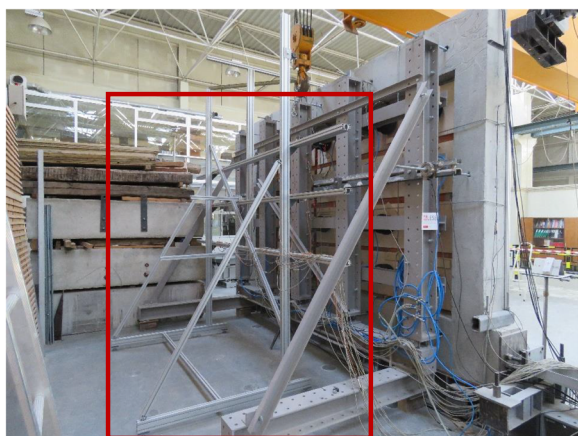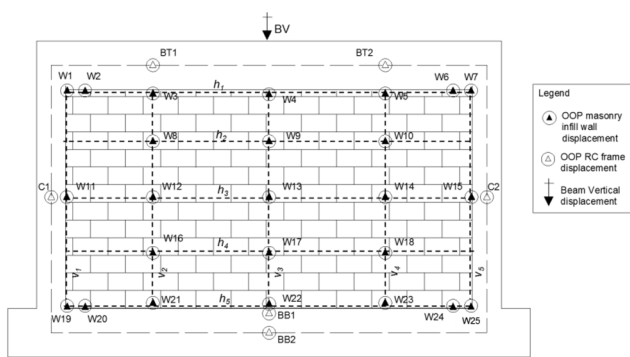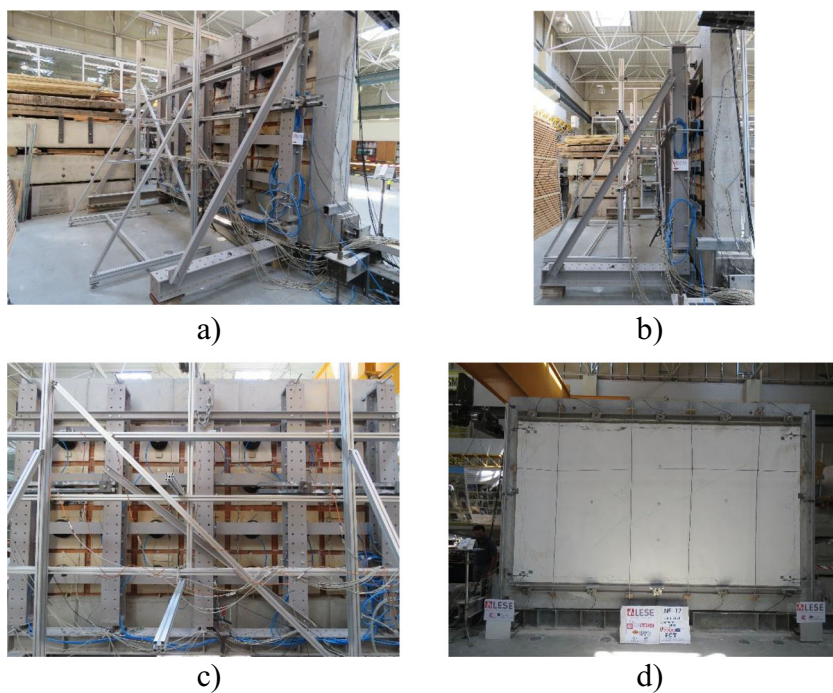

a)

b)

c)

d)

a)

b)

Fig. 10 – Instrumentation: (**a**) schematic front layout; and (**b**) general view

the RC frame in twelve points (5 in the bottom beam, 5 in the top beam, and two in middle-height columns) with steel bars that are coupled with load cells to allow monitoring the OOP loadings. Figure 8(a), (b) show the schematic layout and the general view of the test setup.

The pneumatic actuators performed the panel loading, the control is performed by monitoring their internal pressure and the imposed OOP displacements in a selected control point. General views of the testing setup are shown in Fig. 9.

Control System Description

The control system is similar to those described in the previous sub-section, and is composed of two main components: (i) pneumatic actuators control; and (ii) axial load control. One electronic proportional directional control valves (0-10 bar), one air compressors (100lt, 10 bar), one manual filter pressure regulator (0-16 bar) and two transducers (for pressure and displacement) compose the pneumatic actuator control. The air compressor is connected to the pressure regulator (limit defined as 2 bar) and the electronic valve. The panel loading was achieved by the pneumatic actuators air entrance control, by monitoring their internal pressure and their imposed OOP displacements.

Instrumentation

A few modifications were introduced namely: 25 displacement transducers were used to measure the OOP
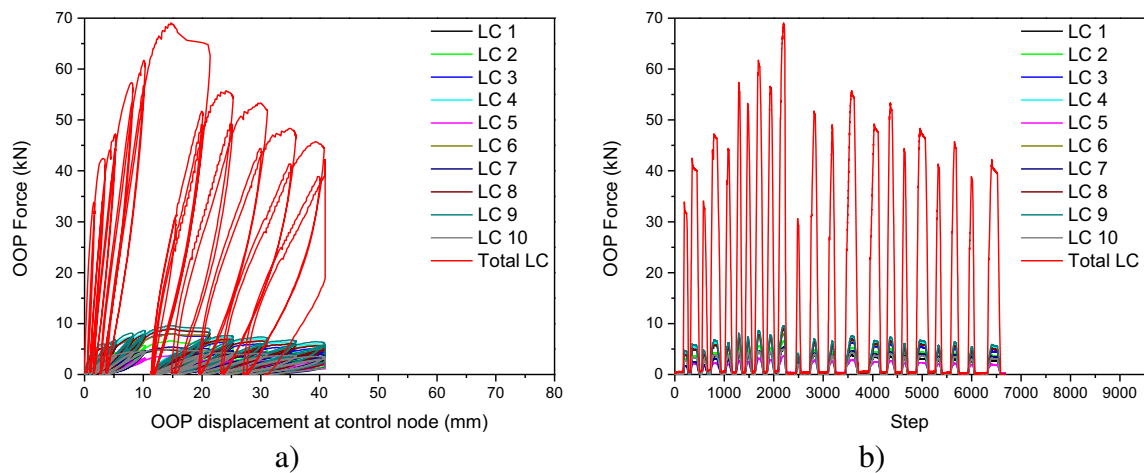
Fig. 11 - OOP cyclic test result using pneumatic actuators: (**a**) force-displacement curves; and (**b**) OOP force evolution

displacements of the panel along five horizontal and vertical alignments; the detachment of the infill panel from the surrounding corners was measured by LVDT's placed in the transition infill plane-frame; six displacement transducers monitored the OOP displacements of columns and beams. Additionally, the vertical displacements of the top beam were measured by one LVDT placed at mid-span to monitor the evolution of possible arching mechanism (Fig. 10(a)). The support/reference structure for the monitoring system was placed behind the wall, as shown in Fig. 10(b), which allow carrying out tests until panel collapse or until reaching the limit capacity of the pneumatics' extension (100 mm).

The loading protocol consisted on the application half-cyclic OOP displacements (loading-unloading-reloading) that were imposed with steadily increasing displacement levels, targeting the following nominal peak displacements at the control node located in the centre of the panel: 0.5, 1, 1.5, 2, 2.5, 3.5; 5; 7.5; 10 mm; and then 5 by 5 mm up to a maximum OOP displacement of 120 mm. Two half-cycles were repeated for each lateral deformation demand level.

Examples of Application

Full infill wall without opening

One specimen with the same geometry of the models described in the previous section was built with a thin layer of mortar plaster (around 1 cm). The primary purpose was to validate this new test setup and assess the performance of the pneumatic actuators to perform cyclic tests and to mobilize the global MIW. The test force-displacement curves are plotted in Fig. 11(a), from which it can be observed that the cyclic test was performed successfully, achieving the maximum strength of 69kN for 11.5 mm OOP displacement. The evolution of the individual load cells throughout the test, shown in Fig. 11(b), evidenced a very similar behaviour, which means that the entire wall surface is being subjected to the same OOP pressure.

Another MIW was subjected to OOP loadings using pneumatic jacks, where the primary goal was to reach the collapsed state. One of the significant advantages of using this test setup

Fig. 12 - OOP cyclic test result of a MIW without opening using pneumatic actuators: (**a**) force-displacement curves; and (**b**) OOP force evolution

a)   b)

is the ability to achieve this goal without damaging instrumentation and observing all the mechanism. For example, Fig. 12(a) shows the beginning of the collapse mechanism of one specimen. The cracking pattern is a trilinear one, however, for higher OOP displacement demands it occurred the sliding of the panel from the top and bottom beams, which resulted in the panel collapse (see Fig. 12(b)).

As-built infill wall with an opening

Recently, the OOP testing of MIW with openings has started tested, which is a particular topic not covered in the literature. For example, in Fig. 13 it is presented the test of MIW with dimensions 4.20×2.30 m (length x height) with a central opening with dimensions 1.15×1.15 m. The pneumatic jacks located at the area of the opening were turned off and removed from the structure, and the OOP loading was applied along the panel surface. This test setup can test infill walls with openings with different configurations and geometric dimensions as well as multiple openings. Figure 13 shows the moment when it occurred the first significant crack, a diagonal one from the bottom corner of the opening to the middle height of the spandrel (left side) and the bottom of the spandrel (right side). After reaching the maximum force, the right spandrel of the MIW suddenly collapsed, as shown in Fig. 13(b). The test was carried out until reaching the total collapse of the left spandrel (see Fig. 13(c)).
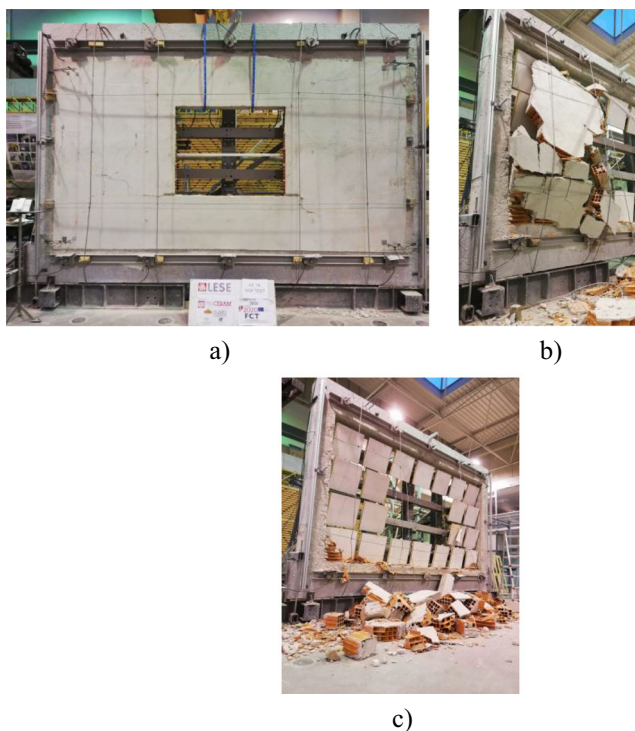

a)

b)

c)

Fig. 13 - OOP cyclic test result of a MIW with opening using pneumatic actuators: (**a**) appearance of first cracking; (**b**) collapse mechanism of the lateral spandrel; (**c**) total collapse view

Final Remarks and Future Challenges

The experimental characterization of the MIW seismic behaviour is nowadays one of the most important topics in seismic engineering. Several research groups are making multiple efforts towards clarifying the considerable influence of many factors in the OOP response of MIW such as the panel slenderness, aspect ratio, and reduction of the panel support width, previous damage caused by previous IP test, openings and workmanship. Quasi-static, pseudo-dynamic and dynamic tests are used for that. Different loading approaches are adopted for the OOP loading application, namely the use of airbags for distributed loads or the use of hydraulic actuators for applying in two, four or eight points of the panel. Different advantages and disadvantages are associated with each one, depending on the authors' interest and objectives.

Along with this manuscript, it was presented the development process of two test setup in the Laboratory for Earthquake and Structural Engineering, one with airbags and one with pneumatic actuators. It was observed that the use of airbags restricts the panel geometry and typology (with or without openings). The concept of a self-equilibrated system allows to monitoring the stress concentration along with the panel and thus understanding the response mechanism of the wall. The use of small pneumatic jacks is an innovative approach to apply distributed loadings, allowing the realization of tests in MIW with openings (different dimensions and multiple loadings). The second advantage is the possibility of the positioning of the instrumentation in the backside of the panel, which allows performing the test until reaching the collapse.

The characterization of the interaction between the MIW in-plane and OOP behaviour is still the biggest challenge in the experimental characterization of MIW. Nowadays, this characterization is achieved by performing independent tests, namely, first the IP test imposing a certain level of drift (and corresponding damage). After that, the OOP test is carried out. Combined IP-OOP quasi-static tests are needed to characterize this behaviour interaction better, and it is crucial to assess in which way the OOP damage affects the IP behaviour of the wall. It is essential to clarify the IP-OOP drift limit interaction curve for panels with and without openings.

Compliance with Ethical Standards

Conflict of Interest The authors whose names are listed in the paper certify that they have no Conflicts of Interest or involvement in any

organization or entity with any financial interest, or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

References

1. Romão X et al (2013) Field observations and interpretation of the structural performance of constructions after the 11 May 2011Lorca earthquake. Eng Fail Anal 34:670–692

2. Hermanns L, Fraile A, Alarcón E, Álvarez R (2014) Performance of buildings with masonry infill walls during the 2011 Lorca earthquake. Bull Earthq Eng 12:1977–1997

3. Furtado A, Costa C, Arêde A, Rodrigues H (2016) Geometric characterisation of Portuguese RC buildings with masonry infill walls. Eur J Environ Civ Eng:1–16

4. Lee HS, Woo SW (2002) Effect of masonry infills on seismic performance of a 3-storey R/C frame with non-seismic detailing. Earthquake Engng Struct Dyn 31:353–378. https://doi.org/10.1002/eqe.112

5. Vicente R, Rodrigues H, Varum H, Costa A, Mendes da Silva R (2012) Performance of masonry enclosure walls: lessons learned from recent earthquakes," (in English). Earthq Eng Eng Vib 11(1):23–34

6. Dawe J, Seah C (1989) Behaviour of masonry infilled steel frames. Can J Civ Eng 16:865–876

7. De Risi MT, Di Domenico M, Ricci P, Verderame GM, Manfredi G (2019) Experimental investigation on the influence of the aspect ratio on the in-plane/out-of-plane interaction for masonry infills in RC frames. Eng Struct 189:523–540

8. Ricci P, Di Domenico M, Verderame GM (2018) Experimental investigation of the influence of slenderness ratio and of the in-plane/out-of-plane interaction on the out-of-plane strength of URM infill walls. Constr Build Mater 191:507–522

9. Di Domenico M, Ricci P, Verderame GM (2018) Experimental assessment of the influence of boundary conditions on the out-of-plane response of unreinforced masonry infill walls. J Earthq Eng: 1–39

10. Akhoundi F, Vasconcelos G, Lourenço P (2018) Experimental out-of-plane behavior of brick masonry Infilled frames. Int J Architectural Herit 14(2):221–237

11. Moghaddam H, Dowling P, Ambraseys N (1988) Shaking table study of brick masonry infilled frames subjected to seismic actions. Presented at the world conference on earthquake engineering - 9WCEE, Tokyo

12. Dawe J, Seah C (1989) Out-of-plane resistance of concrete masonry infilled panels. Can J Civ Eng 16(6):854–864

13. Angel R, Abrams D, Shapiro D, Uzarski J, Webster M (1994) Behavior of reinforced concrete frames, with masonry infills, civil engineering studies, Reserach series no. 589, UILU-ENG. Department of Civil Engineering, University of Ilinois, USA, pp 94–2005

14. Beconcini M (1997) Sulla resistenza a forze orizzontali di pareti in elementi forati in laterizio. Construire in laterizio 55:60–69

15. Flanagan R, Bennett R (1999) Bidirectional behaviour of structural clay tile infilled frames. J Struct Eng 125(3):236–244

16. Calvi G, Bolognini D (2001) Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels. J Earthq Eng 5(2):153–185

17. Varela-Rivera J, Polanco-May M, Fernandez-Baqueiro L, Moreno E (2012) Confined masonry walls subjected to combined axial loads and out-of-plane uniform pressures. Can J Civ Eng 39:439–447

18. Pereira P, Pereira M, Ferreira J, Lourenço P (2012) Behavior of masonry infill panels in RC frames subjected to in plane and out

19. Hak S, Morandi P, Magenes G (2014) Out-of-plane experimental response of strong masonry infills. Presented at the second European conference on earthquake engineering and seismology - 2ECEES, Turkey

20. da Porto F, Guidi G, Verlato N, Modena C (2015) Effectiveness of plasters and textile reinforced mortars for strengthening clay masonry infill walls subjected to combined in-plane/out-of-plane actions / Wirksamkeit von Putz und textilbewehrtem Mörtel bei der Verstärkung von Ausfachungswänden aus Ziegelmauerwerk, die kombinierter Scheiben- und Plattenbeanspruchung ausgesetzt Sind, Mauerwerk, vol. 19, no. 5, pp. 334–354

21. Furtado A, Rodrigues H, Arêde A, Varum H (2016) Experimental evaluation of out-of-plane capacity of masonry infill walls. Eng Struct 111:48–63

22. Mosoarca M, Petrus C, Stoian V, Anastasiadis A (2016) Behaviour of masonry infills subjected to out of plane plane seismic actions part 2: experimental testing. Presented at the international brick and block masonry conference - IB2MAC, Padua

23. Silva L, Vasconcelos G, Lourenço P, Akhoundi F (2016) Experimental evaluation of a constructive system for earthquake resisting masonry infill walls. Presented at the brick and block masonry conference (IB2MAC), Padua

24. Liauw T, Kwan K (1992) Experimental study of shear wall and infilled frame on shake-table. Presented at the world conference on earthquake engineering - 10WCEE, Madrid

25. Klingner R, Rubiano N, Bashandy T, Sweeney S (1996) Evaluation and analytical verification of shaking table data from infilled frames. Presented at the world conference on earthquake engineering - 11WCEE, Acapulco

26. Fardis M, Bousias S, Franchioni G, Panagiotakos T (1999) Seismic response and design of RC structures with plan-eccentric masonry infills. Earthq Eng Struct Dyn 28:173–191

27. Zarnic R, Gostic S, Crewe A, Taylor A (2001) Shaking table tests of 1:4 reduced scale models of masonry infilled reinforced concrete frame buildings. Earthq Eng Struct Dyn 30:819–834

28. Corte G, Fiorinho L, Mazzolani F (2008) Lateral-loading tests on a real RC building including masonry infill panels with and without FRP strengthening. J Mater Civ Eng 20(6):419–431

29. Komaraneni S, Rai D, Eeri M, Singhal V (2011) Seismic behavior of framed masonry panels with prior damage when subjected to out-of-plane loading. Earthquake Spectra 27(4):1077–1103

30. Stavridis A, Koutromanos I, Shing P (2012) Shake-table tests of a three-story reinforced concrete frame with maosnry walls. Earthq Eng Struct Dyn 41:1089–1108

31. Tondelli M, Beyer K, DeJong M (2016) Influence of boundary conditions on the out-of-plane response of brick masonry walls in buildings with RC slabs. Earthquake Engng Struct Dyn 45:1337–1356. https://doi.org/10.1002/eqe.2710

32. Furtado A, Rodrigues H, Arêde A, Varum H (2018) Out-of-plane behavior of masonry infilled RC frames based on the experimental tests available: a systematic review. Constr Build Mater 168:831–848

33. Furtado A, Rodrigues H, Arêde A, Varum H (2018) Effect of the panel width support and columns axial load on the infill masonry walls out-of-plane behavior. J Earthq Eng:1–29

34. Mosallam AS (2007) Out-of-plane flexural behavior of unreinforced red brick walls strengthened with FRP composites. Compos Part B 38:16

35. Griffith M, Vaculik J, Lam N, Wilson J, Lumantarna E (2007) Cyclic testing of unreinforced masonry walls in two-way bending. Earthq Eng Struct Dyn 36:801–821

36. Griffith M, Vaculik J (2007) Out-of-plane flexural strength of unreinforced clay brick masonry walls. TMS J 25(1):53–68

37. Ferreira T, Costa AA, Arêde A, Varum H, Costa A (2016) *In situ* out-of-plane cyclic testing of original and strengthened traditional stone masonry walls using airbags. Abstr J Earthq Eng 20(5):749–772

38. Silva L (2017) Experimental and numerical study of new systems for earthquake resistant masonry enclosures in reinforced concrete buildings, research thesis project. Department of Civil Engineering, University of Minho, Guimarães

39. Lunn DS, Rizkalla SH (2011) Strengthening of infill masonry walls with FRP materials. J Compos Constr 15(2):206–214

40. Di Domenico M, Ricci P, Verderame GM (2019) Predicting the out-of-plane seismic strength of unreinforced masonry infill walls. J Earthq Eng 1–38. https://doi.org/10.1080/13632469.2019.1604453

41. Bitter R, Mohiuddin T, Nawrocki M (2006) LabVIEW: Advanced programming techniques. Crc Press