Proceedings of the 6th International Conference on Mechanics and Materials in Design,
Editors: J.F. Silva Gomes & S.A. Meguid, P.Delgada/Azores, 26-30 July 2015

PAPER REF: 5765

IN-PLANE AND OUT-OF PLANE EXPERIMENTAL CHARACTERIZATION OF RC MASONRY INFILLED FRAMES

Farhad Akhoundi, Graça Vasconcelos, Paulo Lourenço, Carlos Palha, Luis Silva
Institute for Sustainability and Innovation in Structural Engineering (ISISE), U. Minho, Guimarães, Portugal
(*)*Email:* farhad.akhoundi@civil.uminho.pt

ABSTRACT

Seismic investigations of typical south European masonry infilled frames were performed by testing two reduced scale specimens: one in the in-plane direction and another in the out-of-plane direction. Information about geometry and reinforcement scheme of those structures constructed in 1980s were obtained by [1]. The specimen to be tested in the in-plane direction was constructed as double leaf masonry while the specimen for testing in the out-of-plane direction is constructed with only its exterior leaf since the recent earthquakes have highlighted the vulnerability of the external leaf of the infills in out-of-plane direction [2]. The tests were performed by applying the pre-defined values of displacements in the in-plane and out-of-plane directions in the control points. For in-plane testing it was done by hydraulic actuator and for out-of-plane testing through the application of an airbag. Input and output air in the airbag was controlled by using a software to apply a specific displacement in the control point of the infill wall. Mid-point of the infill was assumed as a control point for out-of-plane testing.

Deformation and crack patterns of the infill confirm the formation of two-way arching mechanism of the masonry infill until collapse of the upper horizontal interface between infill and frame which is known as weakest interface due to difficulties in filling the mortar between bricks of last row and upper beam. This results in the crack opening through a well-defined path and the consequent collapse of the infill

Keywords: Masonry Infill walls, In-Plane, Out-of-Plane, Displacement Control, Airbag.

INTRODUCTION

The interaction of the masonry infill walls with its surrounding frame was the major concern of the researchers since more than 50 years ago. Recent earthquakes such as Mexico City earthquake in 1985 [3], Bhuj earthquake in 2001 [4], L'Aquila earthquake in 2009 [2] have confirmed that masonry infills can affect the global and local behavior of the reinforced concrete (RC) or steel frames.

This influence can be positive or negative in the in-plane direction. When it is positive it means that the presence of masonry infills improves the strength and stiffness of the structure to resist the lateral load such as earthquakes. The negative influence which is not the scope of this study mainly relates to the formation of soft story and short column phenomena, which can result in the global or local failure of the structure. As it is shown in the Figure 1 the formation of the short column phenomenon happens when masonry infills leave a short portion of the column clear, leading to the shear collapse of the columns. The soft story phenomenon can be observed when the distribution of the infill walls along the height of the structure is irregular. Even if there are some cases with uniform distribution of infill panels along the height of the structure, the soft story mechanism appears when a) the ground motion is strong compared to design strength b) the global ductility of the bare frame and structural elements is low c) the infill walls are relatively weak and brittle which is discussed in detail in [5]. Several experimental studies have been made to investigate the behavior of masonry infilled frames, either in reinforced concrete frames [6, 7] or in steel frames [8, 9]. It was investigated that the added walls significantly increase the initial stiffness and lateral strength of the bare frame. Different studies were carried out to find out the parameters that could influence the in-plane behavior of infilled frames [10, 11]. Those parameters can be classified into three different categories: a) geometry and mechanical properties of the infill; b) geometry and mechanical properties of the surrounding frame; c) characteristics of the infill-frame interface.

Fig. 1 - Negative effects of infill panel in structure; soft story mechanism [12] (left), short column mechanism [13] (right)

Out-of-plane collapse of masonry infills within concrete frames has been observed in most of the earthquakes. Although the infill panels are assumed as non-structural elements, their damage or collapse is not desirable, given the consequences in terms of human life losses and repair or reconstruction costs. In addition, this type of damage can limit the immediate occupancy after the earthquake event. Aforementioned earthquakes, highlights the damages developed in the infill walls in relation to the minor cracks observed in the structure. In these cases, it was observed that no immediate occupancy was possible due to the generalized damage in the masonry infills. As it is observed in the Figure 2 the ground motion was not strong enough to cause structural damage but due to improper anchorage and interaction of the infill walls and surrounding frame, the exterior walls tore away and the concrete beam and columns were exposed.

Fig. 2 - Damage in non-structural elements [2]

Different researches have investigated the out-of-plane behavior of infilled frames; some of them performed statically and some dynamically [14] [15]. It was concluded that the out-of-plane response of the infilled frames is affected by different parameters. Among them is the boundary condition between masonry infill and its surrounding frame [14] [16-18]. It was also concluded that infill compressive strength and panel dimensions have significant effect on the ultimate load while presence of central opening (about 20% of infill area) do not affect the ultimate strength but reduces postcracking ductility [14]. A summary of large and reduced scale unreinforced masonry infill testing program is represented in [19]. In the large-scale in-situ airbag pressure testing it was concluded that out-of-plane strength of the infill is many times greater than the predicted values that do not take into account the influence of arching mechanism. Most of the out-of-plane tests were performed monotonically in force controlled method while in the recent study it is intended to apply the out-of-plane load uniformly and quasi-statically in displacement control method.

Experimental Program

Description of the specimen

The reinforced concrete frame considered in the present study is representative of a typical frame belonging to a building from the 1980s in Portugal. The definition of the typical RC frame was based on an extensive work carried out on a database of buildings from the building stock from different cities in Portugal [1]. Due to the limitation in the laboratory, it was decided to test reduced scale specimens (half scale). For this, Cauchy's Similitude Law was considered. Therefore, the geometry of the frame was reduced to half values and the reinforcing scheme was updated so that the relation between resisting bending moments and shear resisting forces could be well correlated between full and half scale frames. The geometry and reinforcement scheme adopted for the half scale RC frame are shown in Figure 3.

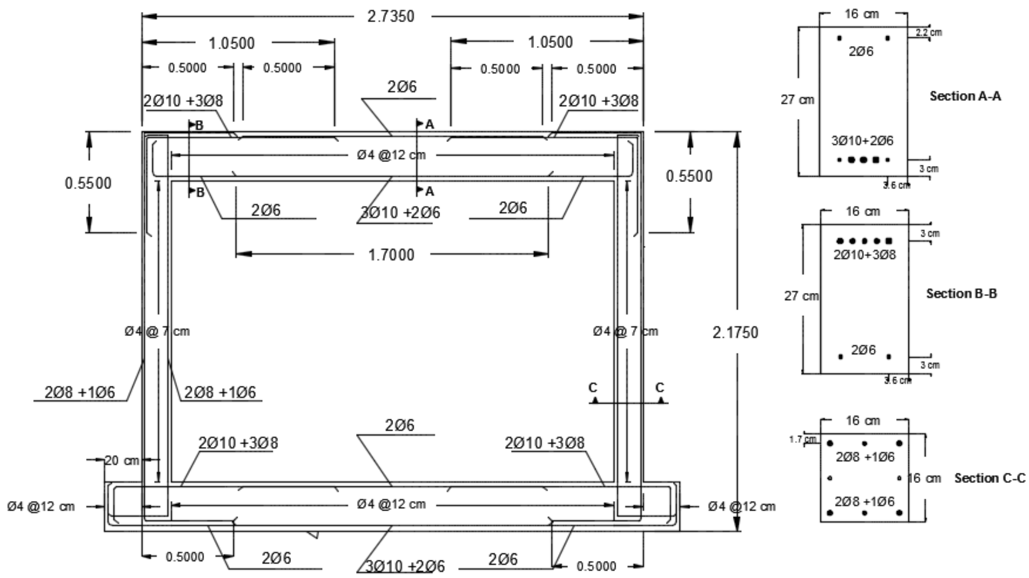


Fig. 3 - Geometry and reinforcement scheme of the RC frame

The masonry panel was built with hollow bricks of 17.5.5x11.5x8cm and 17.5x11.5x6cm (reduced scale bricks) with horizontal perforation, characteristic of the enclosure walls mostly found in Portugal. A M5 mortar was adopted for the laying of the masonry units (bed and head joints). The thickness of the horizontal and vertical mortar joints was assumed to be 1cm. The compressive strength of units and mortar was obtained for the bricks (parallel and horizontal to the holes) and for mortar based on [20, 21] respectively. The results of the average compressive and flexural strength are represented in Table .

Table 1 - Compressive and flexural strength of the bricks and mortar used in the masonry infill wall

Material Properties	Brick	Mortar
Compressive Strength Parallel to the holes (MPa)	4.5	
Compressive Strength Perpendicular to the holes (MPa)	4.09	
Compressive Strength (MPa)		4.3
Flexural Strength (MPa)		1.48

Test Setup and Instrumentation

The test setup for the in-plane loading of the infilled frames is shown in Figure 4. The infilled frame was placed on two separated steel beams of HEA300 that were firmly attached to the strong floor to avoid their sliding on the floor. The sliding of the infilled frame was prevented by bolting an L-shape steel profile to each side of the steel beam and its uplifting was also prevented by bolting two rectangular-shape steel profiles to the steel beams. The rectangular-shape steel profile was made by welding two UNP140. The out-of-plane movement of the enclosure frame was restrained by putting the L-shaped steel frame on each side of the upper beam. Those profiles were bolted to the upper steel beams. Three rollers were placed on upper L-shaped profiles to completely minimize or even eliminate the friction between them and the upper reinforced concrete beam during in-plane loading.

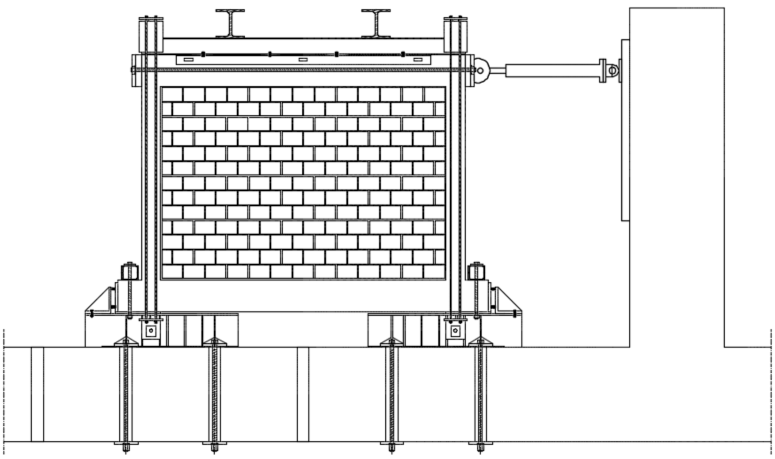


Fig. 4 - Test setup for in-plane cyclic loading

Two vertical jacks were mounted on the top of the columns to apply the vertical load of 80 KN, corresponding to 20% of the column's axial force capacity. Those jacks are pinned to the lower steel beams by means of two vertical rods of φ16. An hydraulic actuator with capacity of 250kN was attached to the reaction wall to apply the in-plane cyclic loading to the specimen. A steel plate of 400x300x30mm^3 was connected to the hydraulic actuator that applies the load in positive direction from right to left direction. This steel plate was connected to other one with the same dimensions by 2φ50 steel rods to enable to pull the specimen in the negative direction. These steel plates enable also to have a uniform distribution of the horizontal load in the cross-section of the upper beam.

An instrumentation scheme to measure the in-plane most relevant displacements during the in-plane testing is shown in Figure 5. Twenty two linear variable differential transformer

(LVDT) devices were used to record the displacement in selected points. From them, four LVDTs were mounted on the masonry infill to measure the deformation of both leaves (L1, L2, L21 and L22), two LVDTs were mounted on the reinforced concrete frame to measure the deformation of the surrounding frame (L19 and L20) and eight LVDTs were used to measure the relative displacement of the infill with respect to its surrounding frame (L3, L4, L5, L6, L7, L8, L9 and L10). The LVDTs L11 and L12 were placed to measure the sliding and uplifting of the infilled frame with respect to the steel profile. Four LVDTs L13, L14, L15 and L16 measure the sliding and uplifting of the steel profiles with respect to the strong floor. LVDTs L17 and L18 measure the horizontal displacement of the upper reinforced concrete frame.

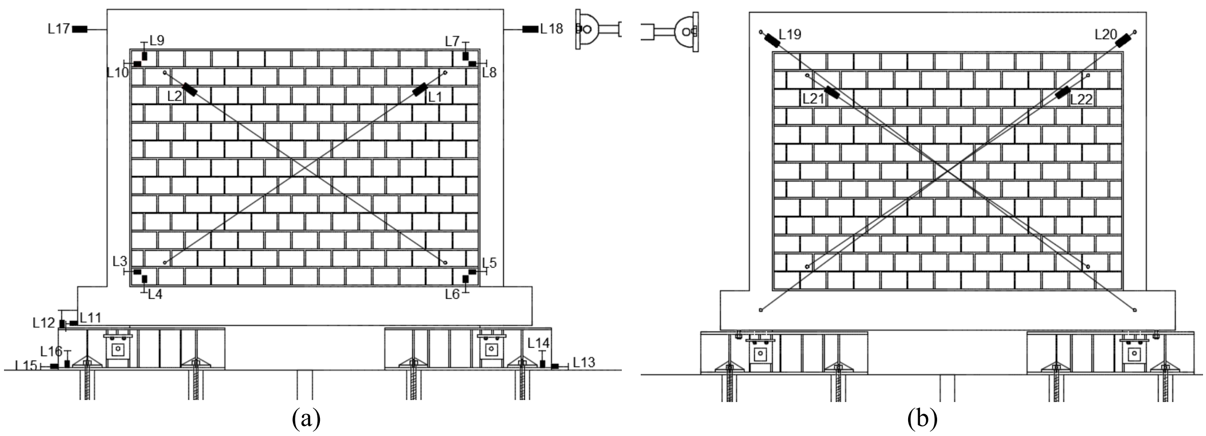


Fig. 5 - Instrumentation plan for in-plane loading; (a) front view; (b) back view

The test setup for out-of-plane loading is shown in Figure 6. The infilled frame was supported on the same steel profiles used for the in-plane testing setup. The out-of-plane restriction at the top and bottom rc beams was strengthened so that out-of-plane displacements at the boundaries could be prevented. For this, four steel rods connected to a steel device, connected in turn to the horizontal steel profiles were added at each side of the top rc beam, see Figure 6.

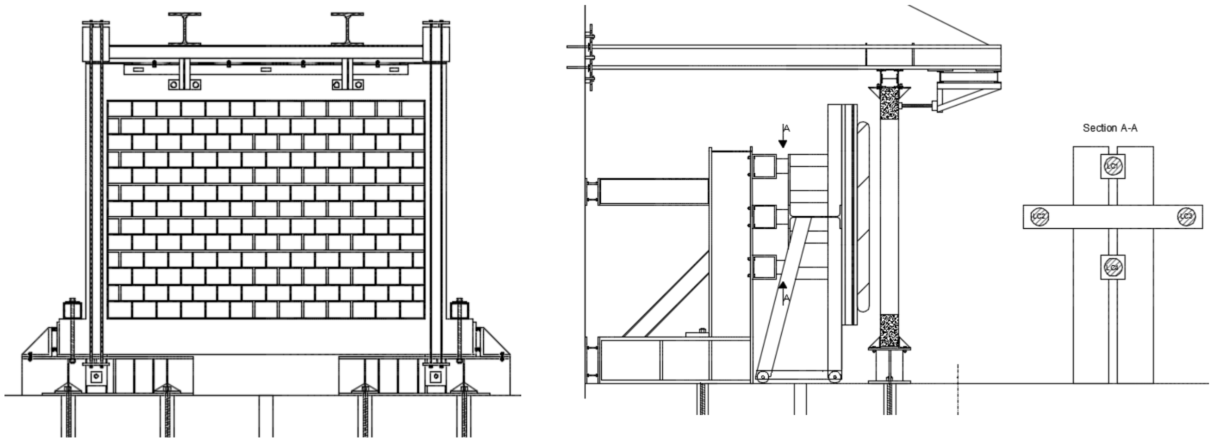
The out-of-plane loading is applied by means of an airbag that is connected to an external supporting frame. Four rollers were mounted in the bottom part of the supporting frame enable its moving along the direction of applied load without friction. The supporting frame was also kept in touch with four loadcells to measure the load that is applied to the infill walls through the airbag, see Figure 6b, where a detail about the system of the four load cells is shown (section A-A). The supporting frame to which the load cells are attached was firmly connected to the strong floor and to the lateral reaction wall, which prevented completely any uplifting and sliding of the out-of-plane reaction structure.

The instrumentation plan of the out-of-plane testing is shown in Figure 7. A total number of fifteen LVDTs were placed on the specimen to monitor its deformation while the out-of-plane load is applied. From them, nine LVDTs record the displacement history of the infill panel during loading (LVDT L1 to L9). Four LVDTs measure the relative displacement between infill and its surrounding frame (L10 to L13) and two LVDTs measure the out-of-plane movement of the upper and bottom reinforced concrete beam (L14 and L15).

Loading pattern for in-plane and out-of-plane tests

The in-plane testing was performed under displacement control by imposing different pre-defined levels of displacement by the hydraulic actuator. The loading protocol for this quasi static cyclic testing of the walls tested (MIF-I-2L(NC)) is shown in Figure 8 in accordance with FEMA 461 [22]. It is composed of fifteen different sinusoidal steps that starts from displacement of 0.5mm (0.03% drift) up to the lateral displacement of 47.63mm, corresponding to a lateral drift of 2.5%. Each step was repeated two times except for the first step that repeated six times. The amplitude a_{i+1} of step $i+1$ is 1.4 times of the amplitude a_i of step i accoedinto to the following expression:

$$a_{i+1} = 1.4 a_i \quad \text{Eq. 1}$$



(a) (b)

Fig. 6 - Test setup for out-of-plane testing: (a) front view; (b) lateral view

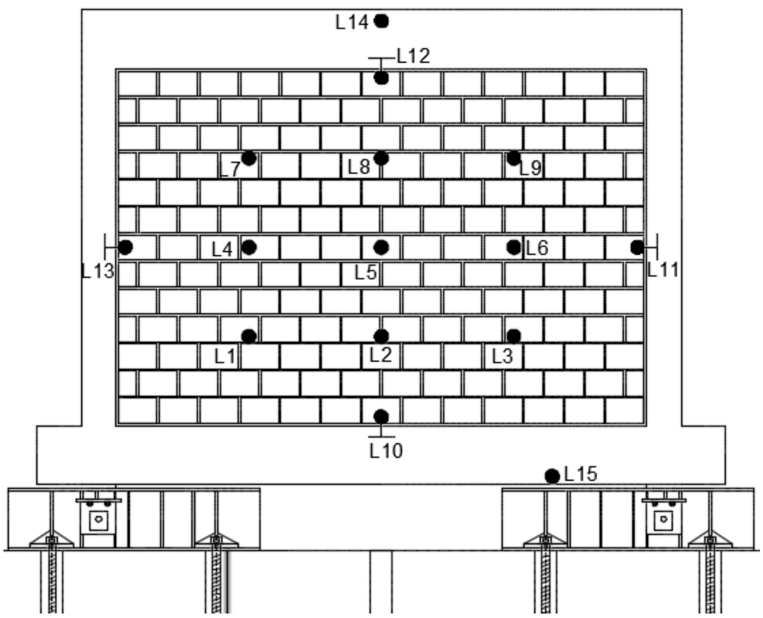


Fig. 7 - Instrumentation plan adopted for the out-of-plane testing

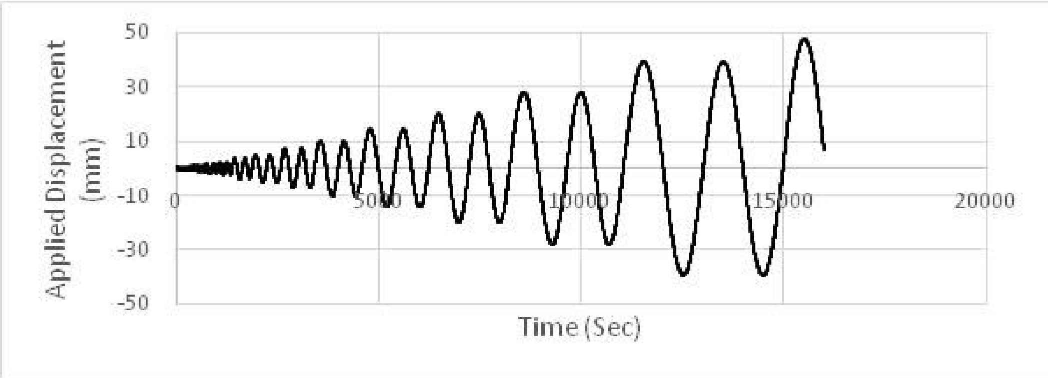


Fig. 8 - Loading protocol for in-plane testing

Figure 9 shows the loading pattern for out-of-plane quasi-static cyclic testing of the specimen defined in the developed software. It is composed of twenty five different amplitudes applied for the selected control point of the infill. The first amplitude repeated for six times and the others repeated two times to investigate the strength degradation of the specimen at each displacement increment. The point selected to control the test was the midpoint of the masonry infill wall (mid height and at mid length).The loading was performed in one direction to monitor the deformation of the infill, propagation of the cracks and performance of the interfaces between infill and reinforced concrete frame.

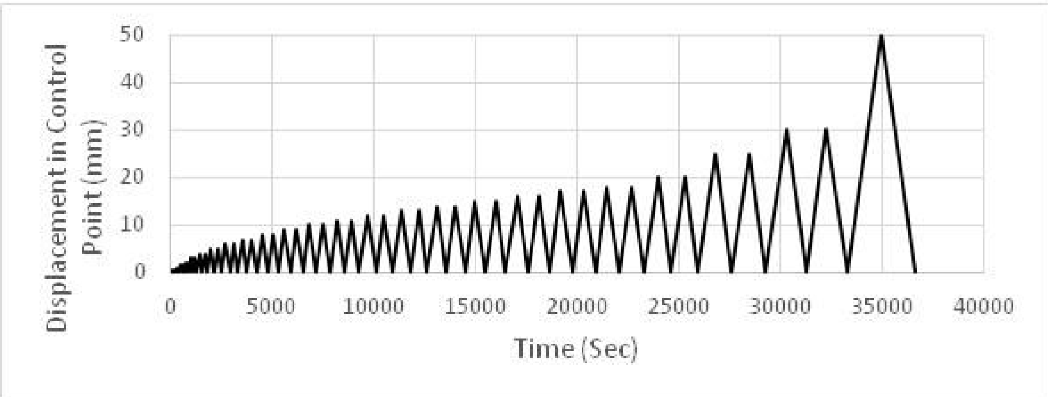


Fig. 9 - Loading pattern applied for wall tested under out-of-plane loading (MIF-O-1L)

RESULTS

In-plane response of the specimen

The lateral force-displacement diagram obtained for the masonry wall MIF-I-2L(NC) during in-plane loading is shown in Figure 10. As mentioned before, positive direction is considered to be the direction where the hydraulic actuator pushes the specimen, whereas the negative direction is the direction that the actuator pulls the specimen by two plates that connected with two thick rods.

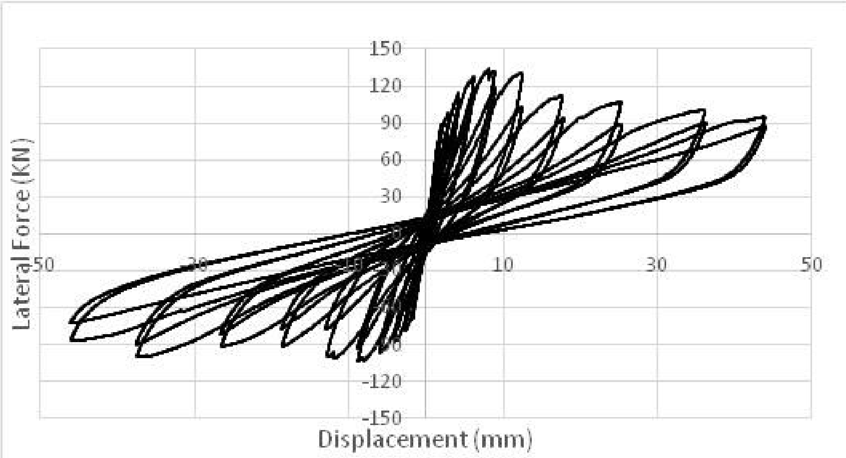
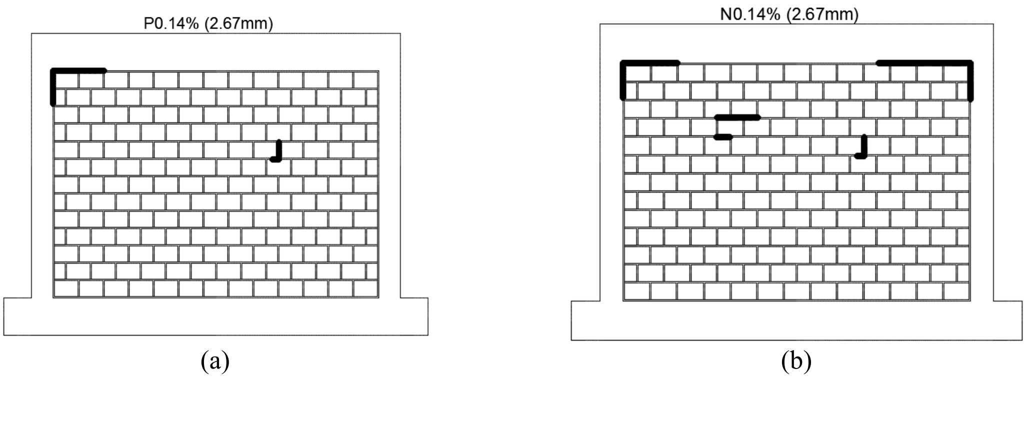


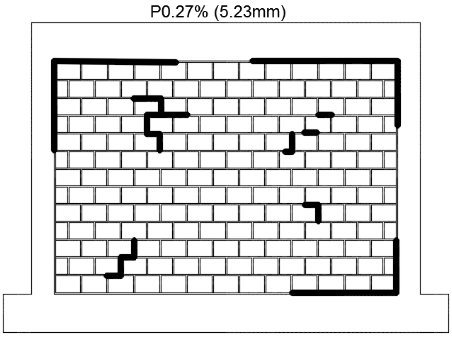
Fig. 10 - In-Plane force-displacement response of the MIF-I-2L(NC)

It is seen that the specimen present some differences in the positive and negative loading directions. In the positive direction, the initial stiffness of the specimen started decreasing at lateral displacement of 2.07mm (0.11% lateral drift) corresponding to lateral force of 85.39KN by cracking the infill in its central part. The specimen reached to the peak load of 133.56KN at displacement of 8.03mm corresponding to lateral drift of 0.42%. After the peak load the lateral force decreased gradually to reach the residual strength of 94.84KN at displacement of 47.63 (2.5% drift). On the other hand, towards the negative direction, initial stiffness of the specimen decreased at displacement of 1.84mm (lateral drift of 0.1%) corresponding to lateral force of 67.32KN. Then the specimen reached its peak load of 103.65KN at displacement of 8.80mm (lateral drift of 0.46%). Lateral force was gradually decreased and reached to 86.35KN at displacement of 47.63 (2.5% drift).

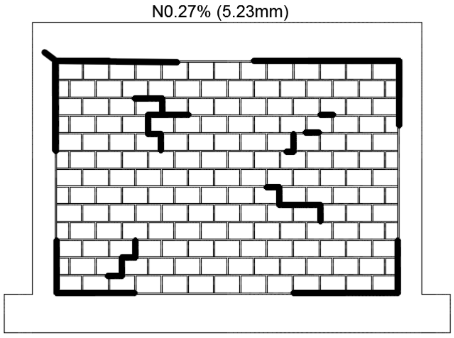
The cracking pattern of the external leaf with thickness of 8cm is shown in Figure 11 and Figure 12. Its cracking initiated at displacement of 2.67mm corresponding to lateral drift of 0.14% in positive direction. In this step, the upper left corner of the infill separated from its bounding frame. In the same lateral drift and at negative direction masonry infill separates from the concrete frame at upper right corner. By increasing the load, the cracks propagate in the diagonal direction as stair stepped cracks passing through mortar joints, see Figure 11c, d. The first flexural cracks in the reinforced concrete frame formed in the lateral drift of 0.27% at leeward column. At lateral drift of 0.38% the cracks propagate in diagonal direction and masonry infill totally separates from its bounding frame, see section Figure 11e,f.



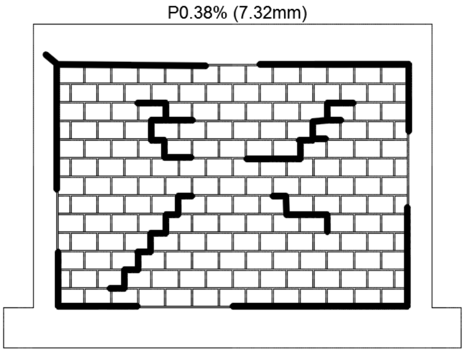
(a) (b)



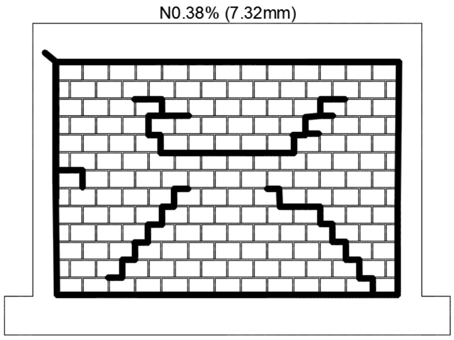
(c)



(d)

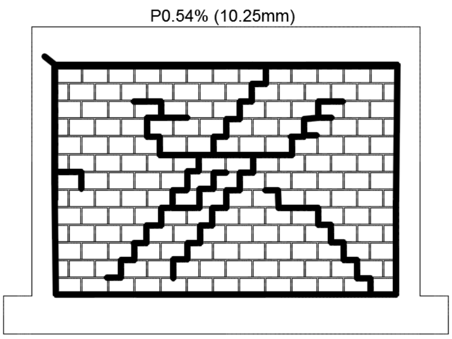


(e)

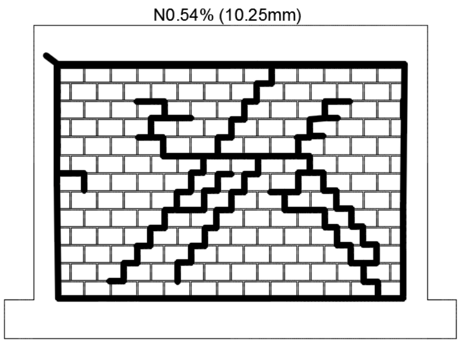


(f)

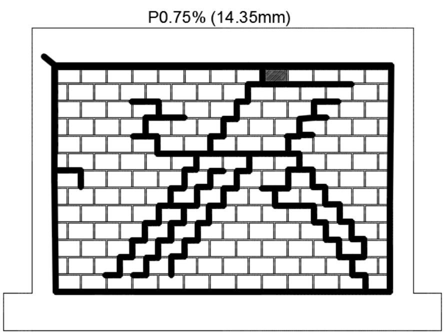
Fig. 11 - Crack propagation in the specimen at lateral drift of; (a)0.14% in positive direction; (b) 0.14% in negative direction; (c)0.27% in positive direction; (d) 0.27% in negative direction; (e)0.38% in positive direction; (f) 0.38% in negative direction



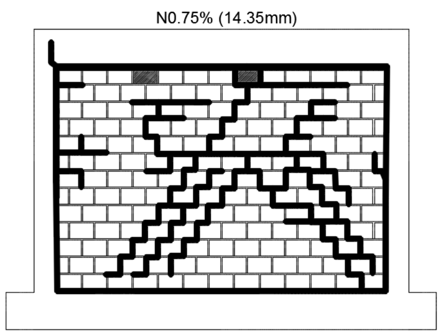
(a)



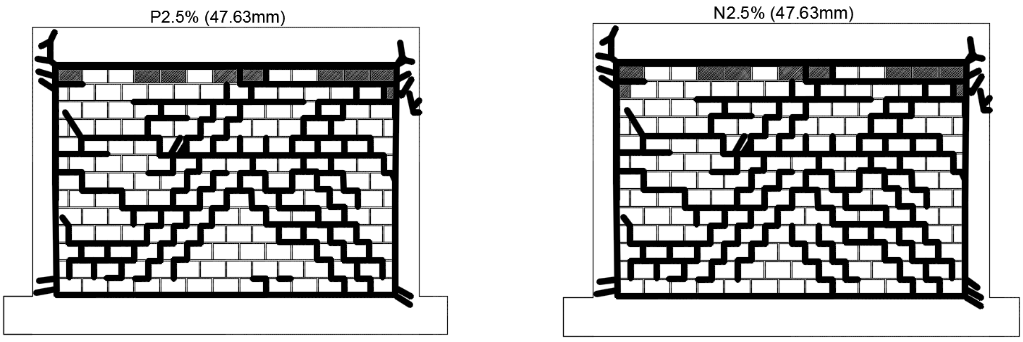
(b)



(c)



(d)



(e) (f)

Fig. 12 - Crack propagation in the specimen at lateral drift; (a) 0.54% in positive direction; (b) 0.54% in negative direction; (c) 0.75% in positive direction; (d) 0.75% in negative direction; (e) 2.5% in positive direction; (f) 2.5% in negative direction

The crack pattern of the specimen at maximum lateral force is shown in Figure 12a,b. The first crushing of the bricks was observed at lateral drift of 0.75% in which by increasing the load, the number of crushed bricks increased and finally at lateral drift of 2.5%, almost the last row the masonry crushed due to high compressive stresses, see Figure 12c-f.

Out-of-plane behavior

The force-displacement diagram obtained for the masonry infill walls for the out-of-plane direction is shown in Figure 13. It is seen that after a an initial linear regime, the wall presents a clear nonlinear behavior before the peak load, presents a plateau at the zone of the maximum resistance and a sudden drop of resistance after a lateral displacement of 25mm. After the displacement of 30mm, it was decided to carry out a monotonic test until the collapse of the wall. It is seen that the maximum displacement reached by the wall is about 50mm. Besides, it is seen that the plastic (residual) deformations increases very slowly during the loading cycles until the displacement of 20mm and increases more between the displacement of 25mm and 30mm and finally for the displacement of 50mm. For these two displacement levels, greater strength and stiffness degradation was observed for the second cycle of loading corresponding to the same displacement.

It is observed that until the displacement of 4mm measured in the control LVDT (central point of the masonry infill wall), no cracks were developed in the wall, see Figure 14.

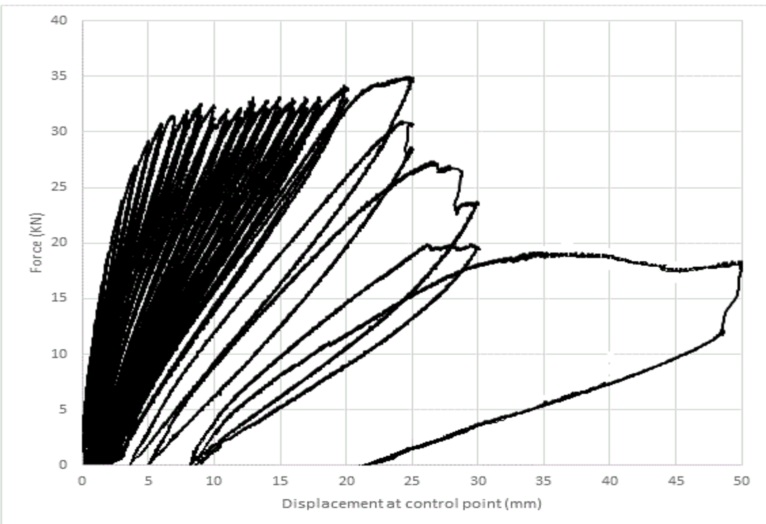


Fig. 13 - Force-displacement diagram for the out-of-plane testing

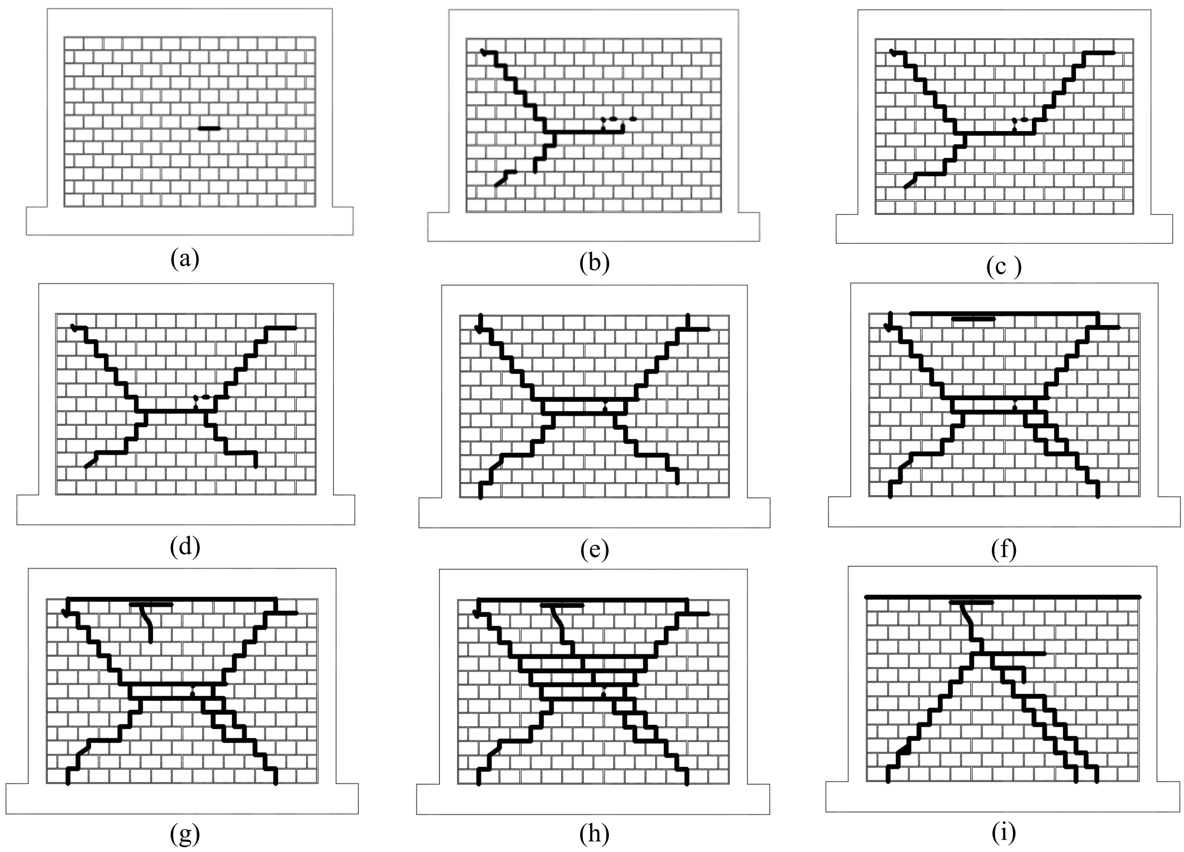


Fig. 14 - Crack pattern of specimen MIF-O-1L at displacement; (a) 5mm (first cycle); (b) 14mm (second cycle ; (c) 15mm (first cycle); (d) 16mm (first cycle); (e) 25mm (first cycle); (f) 25mm (second cycle); (g) 30mm (first cycle); (h) 30mm (second cycle); (i) 50mm

The cracking initiated at the displacement of 5mm by formation of a horizontal small crack at the center of the infill as is shown in Figure 14a. By increasing the load, diagonal cracks formed adjacent to the corners of the infill and connected to the horizontal cracking in the center part of infill. This cracking pattern which is shown in Figure 14d at displacement of 16mm is compatible with cracking pattern of yield line theory of two-way slabs, confirming the formation of two-way arching mechanism. This two-way arching mechanism develops until the collapse or sliding of one of the interfaces due to high compressive or shear stresses. At second cycle of displacement of 25mm, the upper interface between infill and the surrounding frame slid on the loading direction and lose its functionality. After the sliding of the upper interface, the two-way arching mechanism changes to one-way arching mechanism, which leads to the change in the crack pattern of the specimen as shown in Figure 14i. Some of the cracks developed at the displacement of 30mm got closed at displacement of 50mm and are not shown in Figure 14i. This could be related to the changing from the two-way arching mechanism to one-way arching mechanism.

The deformation of the infill masonry wall with respect to the displacement in the control point during the out-of-plane loading is investigated in Figure 15 and Figure 16. As it is shown in Figure 16, the upper and bottom part of the infill have the same deformation until the cracking of the upper interface at the displacement of 25mm in the control point. This is applicable also for right and left part of the infill, see Figure 17. These deformations confirms the symmetric behavior of the infill during the formation of two-way arching mechanism.

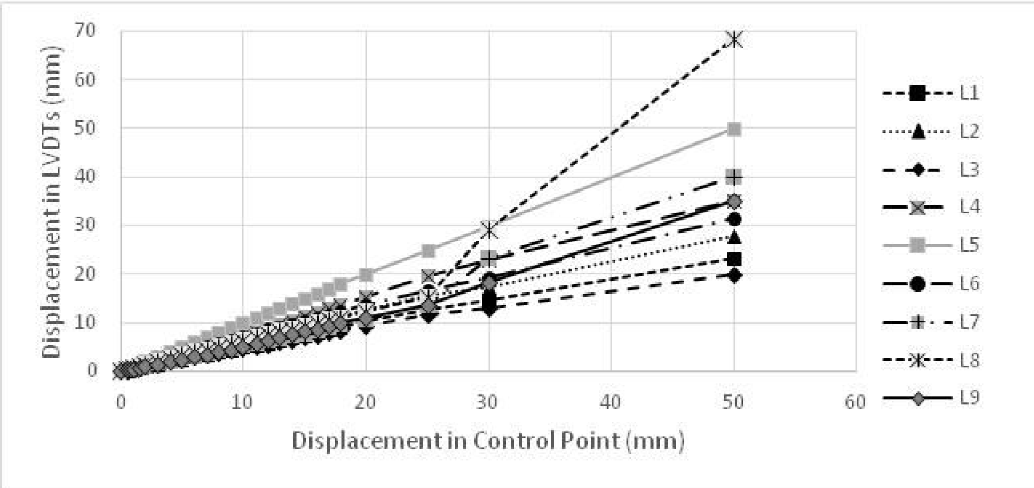


Fig. 15 - Deformation of the infill during out-of-plane loading

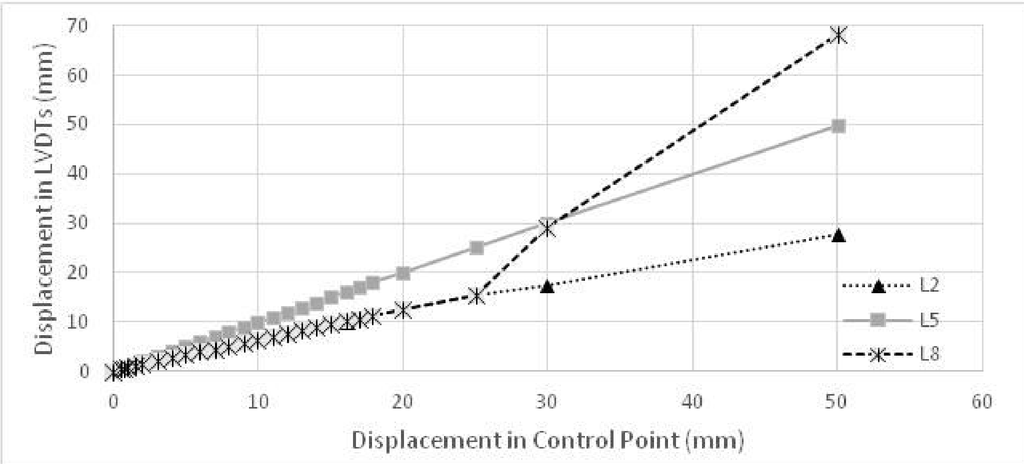


Fig. 16 - Comparison of the deformation at upper and bottom part of the infill (central profile)

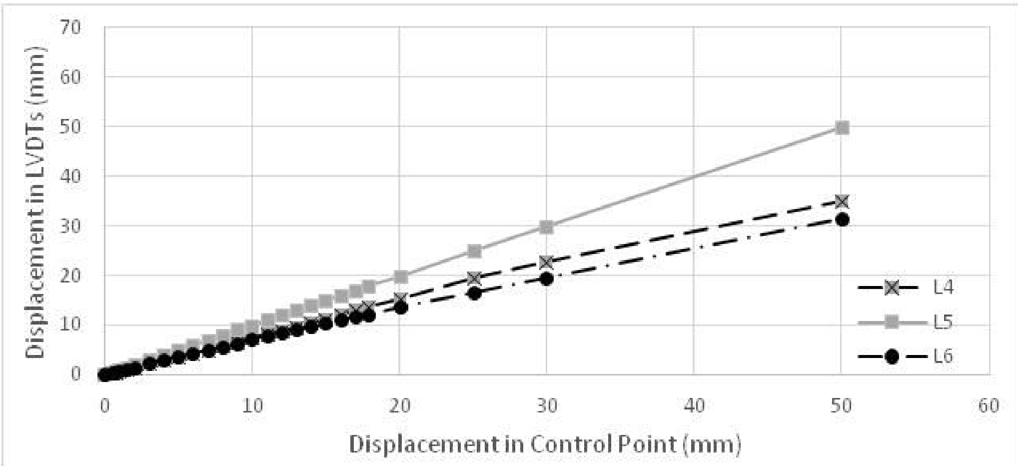


Fig. 17 - Comparison of the deformation at right and left part of the infill

After the cracking of the upper interface and corresponding change of the two-way arching mechanism to one-way horizontal arching mechanism, the upper part of the infill bulges outside and its deformation increases more quickly than the center part of the infill. On the other hand, the left and right part of the infill deforms in a similar way after cracking the upper interface, see Fig and Fig.

CONCLUSION

In this paper, the in-plane and out-of-plane response of typical south European masonry infilled frames were investigated by performing the in-plane and out-of-plane tests.

In the in-plane direction the specimen exhibited an almost symmetric behavior in the positive and negative directions. The separation of the masonry from its bounding frame happened at 0.14% lateral drift and it totally separated at 0.38% lateral drift. Cracking of the specimen started at lateral drift of 0.14% by formation of some small cracks in the mid part of the infill. By increasing the lateral load, the cracks propagated as stair-step cracks passing through the mortar joints. Finally at lateral drift of 0.75% the masonry started crushing due to the high compressive stresses in the infill.

Uniform out-of-plane loading was applied through an airbag to each element of the infill under displacement control method. During the out-of-plane loading, two-way arching mechanism developed, characterizing the resisting mechanism infill under out-of-plane loading. By increasing the load, the upper interface between infill and frame was crushed, leading to the change from the two-way arching mechanism to horizontal arching mechanism. This is associated to the changing of the cracking pattern and also to the dropping down recorded in the force-displacement diagram. After crushing the upper interface, the strength degradation is considerable but is able to reach important lateral out-of-plane displacements.

The earlier crushing of the upper interface between infill and frame could be related to the workmanship and also to the difficulties in filling them with mortar.

ACKNOWLEDGMENTS

The authors are acknowledged to the Portuguese Foundation of Science and Technology for the funding of the project RetroInf – Development of innovative solutions for seismic retrofitting of masonry infill walls (PTDC/ECM/122347/2010).

REFERENCES

[1]-Furtado A, Costa C, Rodrigues H, Arêde A. Characterization of structural characteristics of Portuguese buildings with masonry infill walls stock. 9th International Masonry Conference. University of Minho, Guimarães , Portugal2014.

[2]-Braga F, Manfredi V, Masi A, Salvatori A, Vona M. Performance of non-structural elements in RC buildings during the L'Aquila, 2009 earthquake. Bull Earthquake Eng. 2011;9:307-24.

[3]-Miranda E, Bertero VV. The Mexico Earthquake of September 19, 1985—Performance of Low-Rise Buildings in Mexico City. Earthquake Spectra. 1989;5:121-43.

[4]-Jain SK, Lettis WR, Murty CVR, Bardet JP. Bhuj, India Earthquake of January 26, 2001 Reconnaissance Report. Earthquake Spectra. 2002;Supplement A to Vol 18.

[5]-DolŠEk M, Fajfar P. Soft Storey Effects in Uniformly Infilled Reinforced Concrete Frames. Journal of Earthquake Engineering. 2001;5:1-12.

[6]-Pereira MFP. Avaliação do desempenho das envolventes dos edifícios face à acção dos sismos: Universidade do Minho; 2013.

[7]-Mehrabi AB. Behavior of masonry-infilled reinforced concrete frames subjected to lateral loadings [Ph. D.]: University of Colorado; 1994.

[8]-Mosalam K, White R, Gergely P. Static Response of Infilled Frames Using Quasi-Static Experimentation. Journal of Structural Engineering. 1997;123:1462-4169.

[9]-Dawe JL, Seah CK. Behaviour of masonry infilled steel frames. Canadian Journal of Civil Engineering. 1989;16:865-76.

[10]-Crisafulli F. Seismic Behavior of Reinforced Concrete Structures with Masonry Infills. New Zealand: University of Canterbury; 1997.

[11]-Kakaletsis DJ, Karayannis CG. Influence of Masonry Strength and Openings on Infilled R/C Frames Under Cycling Loading. Journal of Earthquake Engineering. 2008;12:197-221.

[12]-Kusumastuti D. Report on the West Sumatra Earthquake of September 30, 2009. MCEER Bulletin2010.

[13]-Guevara LT, García LE. International network for the design of earthquake resilient cities (INDERC).

[14]-Dawe JL, Seah CK. Out-of-plane resistance of concrete masonry infilled panels. Canadian Journal of Civil Engineering. 1989;16:854-64.

[15]-Angel R, Abrams D, Shapiro D, Uzarski J, Webster M. Behaviour of reinforced concrete frames with masonry infills. Urbana-Champaign, IL, USA1994.

[16]-Dazio A. Effect of boundary conditions on the out-of-plane behavior of unreinforced masonry walls. 14th World Conference on Earthquake Engineering. Beijing, China2008.

[17]-Tu Y-H, Chuang T-H, Liu P-M, Yang Y-S. Out-of-plane shaking table tests on unreinforced masonry panels in RC frames. Engineering Structures. 2010;32:3925-35.

[18]-Dafnis A, Kolsch H, Reimerdes H. Arching in Masonry Walls Subjected to Earthquake Motions. Journal of Structural Engineering. 2002;128:153-9.

[19]-Henderson RC, Fricke KE, Jones WD, E. BJ, Bennett RM. Summary of a Large- and Small-Scale Unreinforced Masonry Infill Test Program. Journal of Structural Engineering. 2003;129:1667-75.

[20]-EN1015-11:1999. Methods of Test for Mortar for Masonry. Part11:Determination of Flexural and Compressive Strength of Hardened Mortar.

[21]-EN772-1:2000. Methods of Tests for Masonry Units. Part1: Determination of Compressive Strength.

[22]-FEMA461. Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components. 2007.