



This is an extended version of the paper presented in SEE7 conference, peer-reviewed again and approved by the JSEE editorial board.

Out-of-Plane Behavior of Masonry Infill Walls

Farhad Akhoundi^{1*}, Graça Vasconcelos², and Paulo B. Lourenço³

1. Assistant Professor, Tabriz Islamic Art University, Tabriz, Iran,

* Corresponding Author; email: f.akhoundi@tabriziau.ac.ir

2. Assistant Professor, ISISE, University of Minho, Department of Civil Engineering, Portugal

3. Professor, ISISE, University of Minho, Department of Civil Engineering, Portugal

Received: 28/01/2017

Accepted: 25/10/2017

ABSTRACT

Past earthquakes have highlighted the vulnerability of masonry infills in the out-of-plane direction. To investigate this vulnerability, it is necessary to test some samples of infills in the out-of-plane direction taking into consideration that the main problem in the simulation of the out-of-plane response is their test setup and calculation of out-of-plane force applied to the infills. One can suggest that multiplying the pressure inside the airbag times its effective area (area of the airbag in full contact with infill) can lead to calculation of the out-of-plane force; but in this paper, it is concluded that the distance between the reaction wall keeping the airbag and the infill affects the effective area of the airbag. When the distance between the reaction walls and the masonry infill wall is smaller, the effective area is closer to the nominal area of the airbag. The effective contact area of the airbag is calculated by dividing the load measured in load cells by the pressure inside the airbag. Based on this result, it is also recommended to use load cells in the test setup to measure the out-of-plane force instead of its calculation by the pressure inside the airbag. After the installation of the out-of-plane test setup, one specimen representing the contemporary construction typology in North of Portugal was tested. In order to investigate its out-of-plane behavior, quasi-static testing was performed on a masonry infill built inside a reinforced concrete frame by means of an airbag system to apply the uniform out-of-plane load to each component of the infill. The main advantage of this testing setup is that the out-of-plane loading can be applied more uniformly in the walls, contrarily to point load configuration. The test was performed under displacement control by selecting the mid-point of the infill as control point. 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. Four load cells were attached to the reaction frame to measure the out-of-plane force. Deformation and crack pattern of the infill confirm the formation of arching mechanism and two-way bending of the masonry infill. Until collapse of the horizontal interface between infill and upper beam in RC frame, the infill bends in two directions. However, the failure of that interface that is known as weakest interface due to difficulties in filling the mortar between bricks of last row and upper beam results in the crack opening through a well-defined path and the consequent collapse of the infill. It is also investigated that the collapse of the infill was happened suddenly unlike the specimens tested by [1]. This is related to the presence of higher axial force on top of the columns in [1] that resulted in formation of a two-way arching mechanism supported on four sides. Besides, it seems that the presence of higher axial force on top of the columns can compensate the defects of upper interface.

Keywords:

Masonry, Infill,
Out-of-Plane, Airbag

1. Introduction

Masonry infills are assumed as non-structural elements and are not considered in the design process of the buildings even if their presence considerably changes the behavior of the buildings.

Its presence could have positive or negative effect on the behavior of the buildings. When it is positive, it means that the presence of masonry infills improves stiffness and lateral strength of the

buildings to resist seismic actions. The negative influence relates mainly to the formation of soft story and short column phenomena, which can result in the global or local failure of the structure. In other words, negative influence of infills are related to the non-uniform distribution of the infills along the height of the structure or when the masonry infills leave a short portion of the column clear, leading to the shear collapse of the columns, see Figure (1).

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.

The earthquakes such as Mexico City earthquake on September 19, 1985 [4], Bhuj earthquake on January 26, 2001 [5] and L'Aquila earthquake on April 6, 2009 [6], 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 in fills. As it is observed in 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.

Out-of-plane failure of the infills can be observed in dividing walls and multi-leaf walls when there is no proper transversal connection between the leaves as it is shown in Figure (3).



Soft Storey Mechanism [2]



Short Column Mechanism [3]

Figure 1. Negative effects of infill within structure.



Figure 2. Damage in non-structural elements [6].



Figure 3. Detachment of the leaves in multi leaf walls [6].

Different researchers have investigated the out-of-plane behavior of masonry walls [7-8]. In [7] 21 full-scale concrete block walls were subjected to uniformly out-of-plane loads applied through the airbag. The effect of different boundary conditions and vertical precompression load were studied. The test was performed monotonically by increasing the pressure inside the airbag. The experimental program of Dawe and Seah [8] included nine full-scale masonry infilled steel frames that were subjected to uniformly distributed lateral pressure that was applied in small increments. The effect of boundary supports, joint reinforcement, panel thickness and presence of opening were investigated, and it was concluded that the infill compressive strength, panel dimension, boundary conditions and rigidity of surrounding frame have a significant effect on the ultimate load while the presence of central opening (about 20% of infill area) do not affect the ultimate strength but reduces post cracking ductility.

In [9], eight single-story, single-bay full-scale infilled frames were tested by applying the sequential in-plane and out-of-plane loading. Two different slenderness ratios (height to thickness of infill) of 11 and 18 were tested for concrete block infills and three of 9, 17 and 34 were tested for clay brick infills. Prior in-plane loading was applied in displacement control manner until cracking of the specimen, and then, the out-of-plane uniform pressure was applied monotonically by means of an airbag to cause failure of the infill. It was concluded that the out-of-plane strength of the infill is affected by the slenderness ratio and depends on the compressive strength of the infill.

A summary of large and reduced scale unreinforced masonry infill testing program is represented in [10]. Some of them were performed statically and some of them dynamically by using a shaking table. 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.

In the sequential testing performed by Calvi et al. [11], the out-of-plane strength of the infill was measured as a function of prior in-plane damage. Out-of-plane forces were applied in a four-point loading configuration monotonically. The effect of putting light reinforcement in the mortar joints or internal plaster were investigated.

It is obvious that in the out-of-plane testing of the specimens carried out by different researchers, the force was applied uniformly or in the point load configuration. In the case of applying the out-of-plane force uniformly by means of an airbag, unfortunately, it is performed monotonically and the cyclic behavior is neglected. In this research, the test setup was installed in a way to apply the out-of-plane force uniformly and cyclically. To do this, the test was performed quasi statically. Input and output air in the airbag was controlled by using a software to apply a specific displacement in the control point (mid-point of the infill) during loading and unloading process.

2. Experimental Program

2.1. Purpose and Overview

The experimental program in the present study

includes two steps; (1) variation of the distance between the reaction frame that keeps the airbag and wooden board inside RC frame to evaluate the influence of this distance on the effective contact area; (2) out-of-plane testing of masonry infill panel built within the RC frame to investigate its out-of-plane behavior. In this test, a cyclic procedure was used, considering the displacement at mid height of the walls as the control point for the imposition of the loading configuration.

2.2. Description of the Specimen

The reinforced concrete frame considered in the present study is representative of a typical contemporary frame used in northern 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 [12]. The geometry and reinforcement scheme of RC frame are shown in Figure (4).

2.3. Characterization of Mechanical Properties

The mechanical properties of the components of the brick masonry used in infill walls tested under in-plane loading is characterized in this section.

2.3.1. Fresh and Hardened Properties of Mortar

The characterization of the mechanical properties of mortar was carried out on specimens casted

with the mortar used in the construction of the brick masonry infill walls. This procedure was followed aiming at evaluating the construction quality. The construction of the masonry infills was carried out by using a premixed mortar of class M5, taking into account that it would be a mortar with a resistance close to the one used in the past decades in the construction of infills in RC buildings. In addition, in order to avoid problems with the quality of mortar, it was decided to use a premixed mortar. In general, a bag of premixed mortar with 25 kg was mixed with 3.5 kg of water by an electrical mixer, following the recommendation of the mortar producer. The sampling of the mortar was carried out during the construction of the masonry infill walls both for the analysis of the consistency [13] and determination of compressive and flexural strength [14].

The results of the consistency, flexural and uniaxial compression tests, namely the flow table, compressive strength, f_m , and flexural strength of mortar, f_p are presented in Table (1). The information about the coefficient of variation is indicated inside brackets. It seems that even if the mixing process of the mortar was controlled during the

Table 1. Consistency, compressive and flexural strength of mortar.

Specimen	Flow Table (mm)	f_m (MPa)	f_r (MPa)
S1	180	3.84 (9.63)	1.48 (8.21)

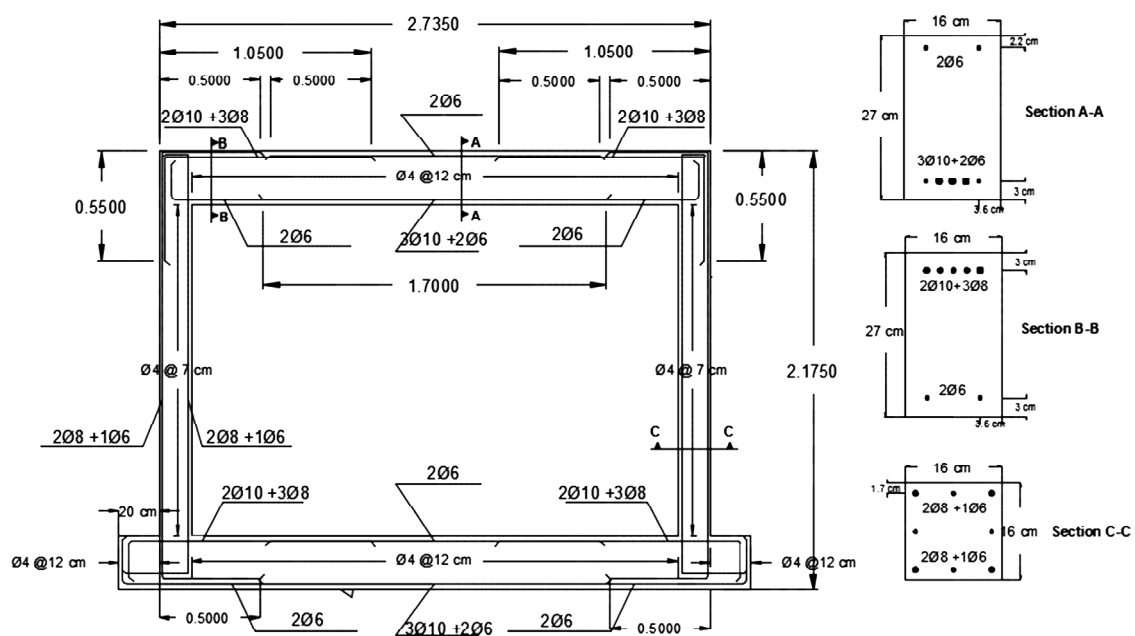


Figure 4. Geometry and reinforcement scheme of the RC frame.

construction of masonry infills, some scatter was found both in fresh and hardened properties.

2.3.2. Dimension of the Bricks

As mentioned before, the units used in the construction of the brick infills were considered with reduced dimensions to comply with the requirements of the reduction in the geometry of the brick infills (half scale infills). In the absence of the possibility to produce reduced scale units in the Portuguese market, it was decided to investigate alternative solutions in Spain. Taking into account that the typical thickness of double leaf brick infills are 15 cm for the external leaf and 11 cm for the internal leaf, it was decided to use brick units produced in Spain with theoretical dimensions of 24.5 11.5 8 cm and 24.5 11.5 6 cm (length height thickness) for the external and internal leaves, respectively. To have the similar height to length ratio of the units of the prototype in the reduced scale units, the length of the bricks was cut to have the length of 17.5 mm. The dimensions of the bricks were measured based on EN772-16:2000 [15] by taking two measurements near the edges of each specimen (length, l_u , height, h_u , thickness, t_u). The dimension of the bricks used in the masonry infill is summarized in Table (2).

Table 2. Measurement of the bricks used in masonry infill.

	Length, l_u	Height, h_u	Thickness, t_u
Average Value	279.12	181.86	151.8

2.3.3. Compressive Strength of the Bricks

The compressive strength of the bricks was obtained according to the European Standard EN-772-1:2000 [16]. For this, nine specimens were prepared in three directions of loading, namely in the direction parallel to the height, parallel to the horizontal perforation and parallel to the thickness. The preparation of the specimens was carried out by capping their surfaces with mortar M10 or polyester, which satisfies the requirements of the standard. The specimens were kept at laboratory environment with almost constant relative air humidity (RH) and temperature (temperature of 20°C and RH close to 65%).

The results of the tests are presented in Table (3) and Table (4). Because it was not possible to place

Table 3. Compressive strength of the bricks used in the infill at different directions.

	Compressive Strength of the Bricks (MPa)
Parallel to the Height	2.75 (27.7)
Parallel to the Length or Perforations	8.17 (3.4)
Parallel to the Thickness	4.86 (15.3)

Table 4. Modulus of elasticity of the bricks used in the infill in direction parallel to the length.

	Modulus of Elasticity of the Bricks (MPa)
Parallel to the Length or Perforations	9805.97 (20.3)

LVDTs on both sides of the bricks to measure the vertical displacements, the elastic modulus of the bricks was not calculated in directions of parallel to the height and thickness.

2.3.4. Compressive Strength of Masonry

The compressive strength and the elastic modulus of the masonry used in the construction of the infill are characterized under compressive loading following the European standards of EN1052-1:1999 [17]. The compressive strength of the masonry was determined by testing three wallets of masonry.

The results of the specimens as average values are represented in Table (5).

Table 5. Average value of modulus of elasticity and compressive strength of masonry.

Sample	Compressive Strength (MPa)	Elastic Modulus (MPa)
	1.59 (4.8)	1258.6 (29.8)

2.3.5. Tensile and Shear Strength of Masonry

Aiming at obtaining the tensile and shear resistance of masonry assemblages, it was decided to carry out diagonal compression tests, following the recommendations of ASTM standard [18]. Diagonal compression tests were performed on three masonry specimens and their results in terms of shear strength and shear modulus are represented in Table (6).

2.3.6. Flexural Behavior of Masonry

The flexural resistance of the brick masonry was

each side of the steel beam. In turn, the uplifting was additionally prevented by bolting two tubular steel profiles to the steel beams. The tubular steel profile was made by welding two UNP140 steel profiles. The out-of-plane movement of the enclosure frame was restrained by putting an L-shaped steel profile of L100 100 10 at each side of the upper concrete beam that was bolted to the top steel frame. Aiming at strengthening the top boundary condition in order to have the top beam adequately restrained to out-of-plane movements, a distinct solution was designed. The top beam was restrained to the out-of-plane movements by using four steel rods M40 attached to a steel triangular structure, connected to two HEB 240 steel profiles that were fixed to the lateral reaction wall. The out-of-plane loading was applied by means of an airbag installed between the masonry infill and the steel frame. The airbag was attached to the steel frame by using a stiff wooden sandwich panel. The steel frame was also connected to the lateral reaction wall and strong floor by rigid L-shaped steel profile of HEB360 to completely prevent its uplifting and sliding during the test. The L-shaped steel profile is stiffened at the top with a horizontal steel profile of HEB220 and with an inclined steel profile of HEB160. The steel frame is connected to the L-shaped steel structure by means of four load cells so that the total force applied by the airbag to the structure could be recorded. The configuration of the load cells is also presented in Figure (5). Four rollers were added on the bottom part of the steel frame to enable its mobility along the horizontal direction without development of friction and erroneous record of the force applied by the airbag.

The instrumentation plan of the specimen for out-of-plane loading is shown in Figure (6). Fifteen

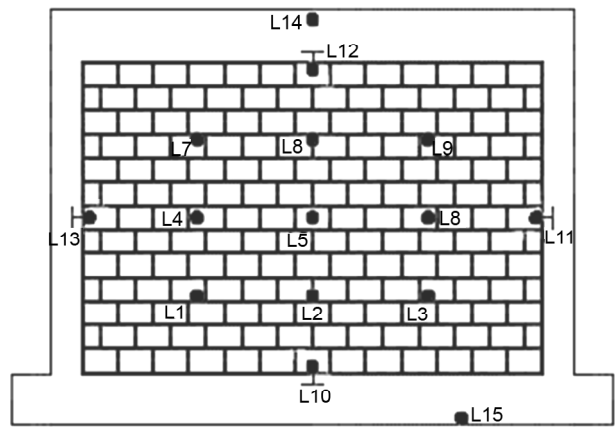


Figure 6. Instrumentation scheme for out-of-plane loading.

LVDTs were mounted on the specimen to measure its displacements from which nine LVDTs (L1 to L9) measure the out-of-plane displacement of the infill, four of them measure the relative displacement between the infill and the surrounding frame (L10-L13) and two LVDTs (L14-L15) measure the out-of-plane movement of the upper and lower RC beams. As described before, the control point is assumed as mid-point of the infill that coincides with LVDT L5.

Loading protocol for the cyclic quasi-static test of masonry infilled frame was shown in Figure (7). Input and output pressure of the airbag was controlled by a software to impose a pre-defined value of the displacement at its specified time in the control point (mid-point of the infill). Loading pattern of the out-of-plane test of the wooden board consisted of five cycles as shown in Figure (8). This decision was made to reduce the execution time of the test because it was not intended to investigate the material properties of the wooden board by applying the loading pattern that was done in masonry infilled frame.

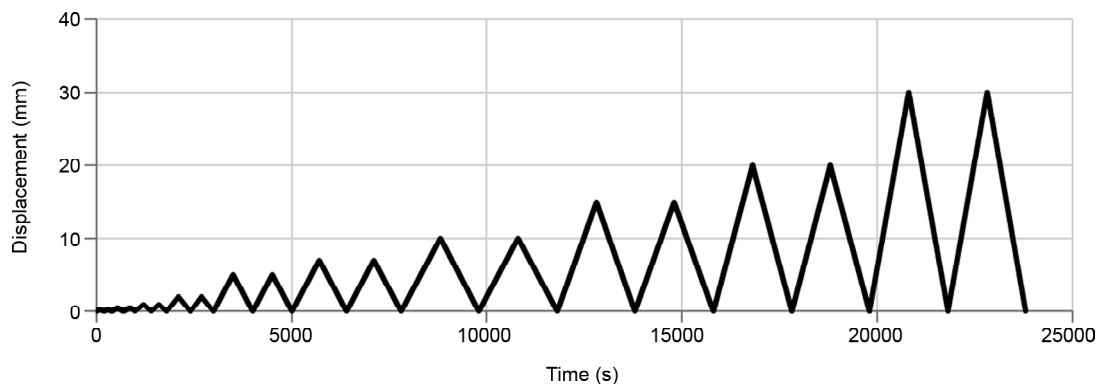


Figure 7. Loading protocol of the out-of-plane testing.

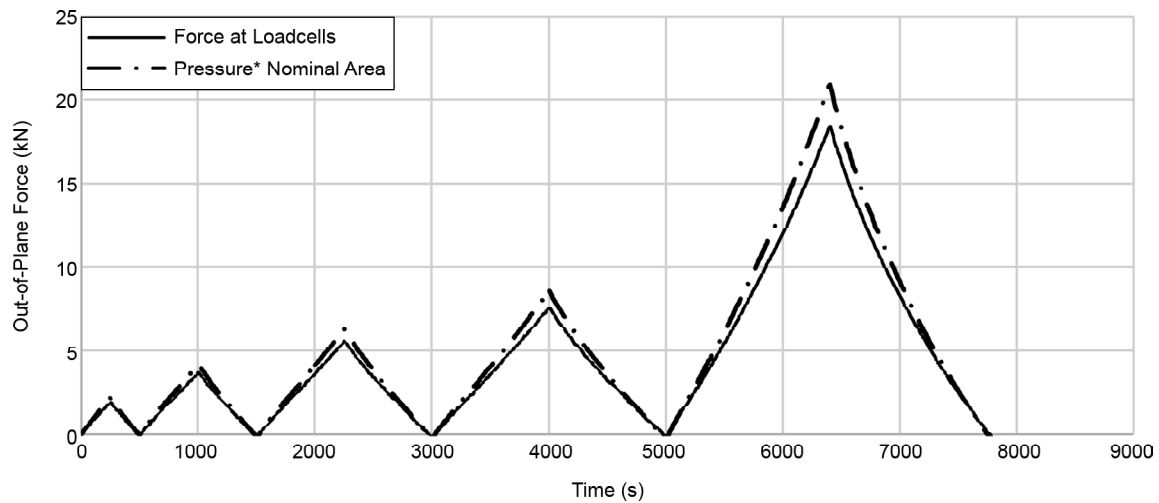


Figure 8. Comparison between the force in the load cells and force calculated by pressure inside airbag for the distance of the airbag of $d=28$ cm.

2.5. Reinforced Concrete Frame with Wooden Board

Wooden board was inserted into a bare frame to study the influence of the distance between supporting frame of the airbag and wooden board on the effective contact area of the airbag on the wooden board. Four distances of 15 cm, 18 cm, 22 cm and 28 cm were investigated, and as it is shown in Figure (8) for the case of $d=28$ cm, the force calculated by multiplying pressure inside airbag times the nominal area is larger than the force measured in the load cells. This means that the effective contact area between airbag and wooden board is less than its nominal area. By comparing the results for $d=15$ cm, 18 cm and 22 cm, it could be concluded that by increasing the distance, the difference between the force measured through load cells and the force calculated by multiplying the pressure inside airbag by its nominal area (3.45 m^2) increases.

This means that the contact area of the airbag with wooden board reduces by increasing its distance from wooden board, see Figure (9). As it is shown in

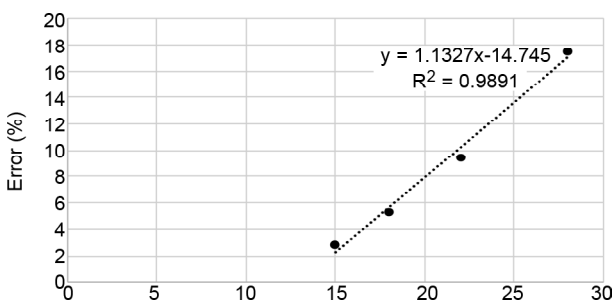


Figure 9. Decrease in effective area of airbag by increasing its distance from wooden board.

Figure (9) where the error calculated as the difference between the nominal contact area of the airbag and the area calculated based on the force measurement in the load cells divided by the pressure inside airbag. The variation of the contact area is practically linear with the distance of the airbag to the wooden board (correlation factor of $R^2=0.9891$).

2.6. Reinforced Concrete Frame with Masonry Infill

The masonry infill was built within the reinforced concrete frame and was subjected to the quasi-static cyclic out-of-plane loading described before. Based on the preliminary study about the influence of the distance of the airbag to the specimens, it was decided to place the airbag at a distance of 15 cm to have the effective area equal to nominal area of the airbag. The cyclic and monotonic force-displacement diagram for the control point (mid-point of the infill) is represented in Figure (10).

The out-of-plane load was applied to the infill and until 2 mm displacement in the control point there was no visible cracks. By increasing the load at the displacement of 5 mm, some visible cracks were observed that were located at the mid-point of the infill in the horizontal direction. At displacement of 7.5 mm, the horizontal crack became thick and more visible. At the displacement around 9.8 mm the upper interface was crushed and the crack pattern composed of a vertical crack connected to diagonal cracks towards the bottom corners was observed, see Figure (11). In this stage, the infill was deformed suddenly until out-of-plane displacement of 33.4 mm.

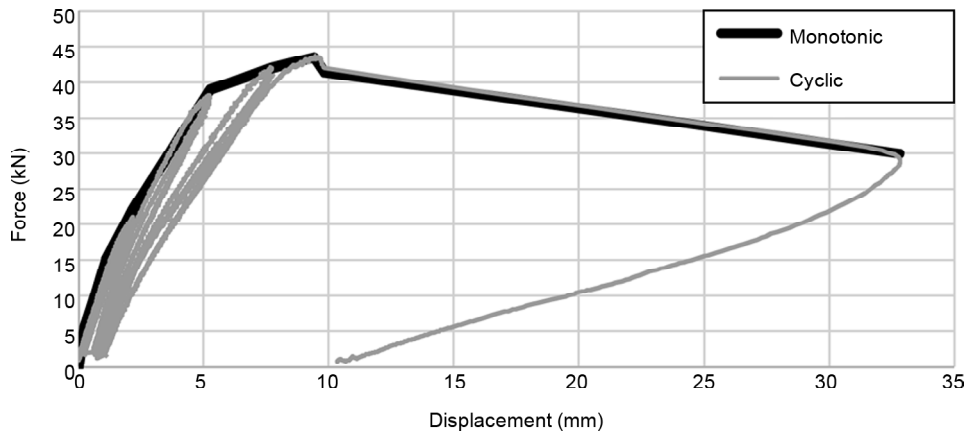


Figure 10. Force-displacement diagram for mid-point of the infill.

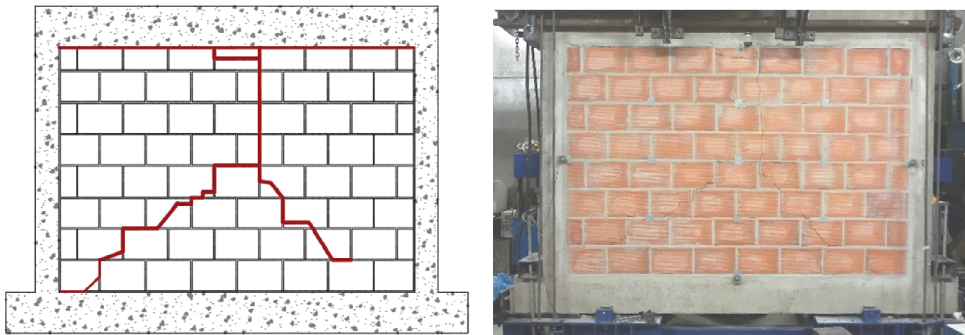


Figure 11. Crack pattern of the infilled frame.

The maximum load corresponding to this failure mechanism was about 45 kN. The final cracking pattern observed in the brick infill wall is totally compatible with the cracking pattern of the yield line theory of the slabs supported on three sides when the upper interface collapses earlier than the other interfaces. Earlier collapses of the upper interface related to the construction difficulties of filling the mortar between brick and upper reinforced concrete beam.

It is also evident that until failure of the specimen at displacement of 9.8 mm, no strength degradation could be observed. This is compatible with the findings of Akhouni [1] as the amount of degradation increases by propagation of the cracks in the specimen.

As explained, the upper interface of the specimens collapsed earlier than other interfaces in the specimen, which resulted in its bulging in the out-of-plane direction. This phenomenon changed the cracking pattern of the specimen with respect to what was observed in [1], in which the cracking pattern was compatible with the yield line theory of

the slabs supported on four sides. In those specimens with higher axial force on columns, the upper interface kept its stability until the whole collapse of the infill. It seems that the presence of higher axial forces on top of the columns could have positive effect on out-of-plane response of the specimens.

3. Conclusions

From the out-of-plane tests carried out on the wooden board and masonry infill, it could be concluded that:

- ❖ The distance between airbag and panel has substantial role on the effective contact area of airbag to the extent that by increasing the distance, the effective contact area decreases. This decrease is linear with respect to the distance.
- ❖ It is also recommended to provide load cells in the test setup for the measurement of out-of-plane force instead of its calculation by multiplying the pressure inside the airbag times its nominal area.
- ❖ The out-of-plane behavior of the masonry infill could be assumed as brittle since after the formation of the thin horizontal crack in displacement

of 5 mm, infill panel suddenly collapses at displacement of 9.8 mm.

- ❖ Cracking pattern of the infill pattern confirms that the upper interface could be assumed as the weakest interface among the others due to construction difficulties. This issue leads to the cracking pattern that is compatible with the bases of the yield line theory that the upper interface collapses earlier.
- ❖ It seems that, the brittle response of the specimen can be improved to ductile behavior by the presence of higher axial forces on top of the columns that results in later collapse of the upper interface.

Acknowledgements

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. Akhouni, F. (2016) *Strategies for Seismic Strengthening of Masonry Infilled Reinforced Concrete Frames*. University of Minho.
2. Kusumastuti, D. (2010) *Report on the West Sumatra Earthquake of September 30, 2009*. MCEER Bulletin.
3. Guevara, L.T. and Garcia, L.E. International network for the design of earthquake resilient cities (INDERC).
4. Miranda, E. and Bertero, V.V. (1989) The Mexico earthquake of September 19, 1985-performance of low-rise buildings in Mexico City. *Earthquake Spectra*, **5**, 121-43.
5. Jain, S.K., Lettis, W.R., Murty, C.V.R., and Bardet, J.P. (2002) Bhuj, India Earthquake of January 26, 2001, Reconnaissance Report. *Earthquake Spectra*, Supplement A to Vol 18.
6. Braga, F., Manfredi, V., Masi, A., Salvatori, A., and Vona, M. (2011) Performance of non-structural elements in RC buildings during the L'Aquila, 2009 earthquake. *Bull Earthquake Eng.*, **9**, 307-324.
7. Drysdale, R. and Essawy, A. (1988) Out-of-plane bending of concrete block walls. *Journal of Structural Engineering*, **114**, 121-33.
8. Dawe, J.L. and Seah, C.K. (1989) Out-of-plane resistance of concrete masonry infilled panels. *Canadian Journal of Civil Engineering*, **16**, 854-864.
9. Angel, R., Abrams, D., Shapiro, D., Uzarski, J., and Webster, M. (1994) *Behaviour of Reinforced Concrete Frames with Masonry Infills*. Urbana-Champaign, IL, USA.
10. Henderson, R.C., Fricke, K.E., Jones, W.D., Beavers, J.E., and Bennett, R.M. (2003) Summary of a large- and small-scale unreinforced masonry infill test program. *Journal of Structural Engineering*, **129**(12), 1667-1675.
11. Calvi, G.M. and Bolognini, D. (2001) Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels. *Journal of Earthquake Engineering*, **5**, 153-185.
12. Furtado, A., Costa, C., Rodrigues, H., and Arêde, A. (2014) Characterization of structural characteristics of Portuguese buildings with masonry infill walls stock. *9th International Masonry Conference*. University of Minho, Guimaraes, Portugal.
13. EN1015-3. Methods of test for mortar for masonry- Part 3: Determination of consistence of fresh mortar (by flow table).
14. EN1015-11:1999. Methods of test for mortar for masonry. Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar.
15. EN772-16:2000. Methods of test for masonry units- Part 16: Determination of dimensions.
16. EN772-1:2000. Methods of tests for masonry units. Part 1: Determination of compressive strength.
17. EN1052-1:1999. Methods of test for masonry- Part 1: Determination of compressive strength.
18. E519-02 A. Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages.
19. EN1052-2:1999. Methods of test for masonry- Part 2: Determination of flexural strength.
20. EN1052-3:2003. Methods of test for masonry- Part 3: Determination of initial shear strength.