OUT-OF-PLANE BEHAVIOR OF MASONRY INFILL WALLS

Farhad AKHOUNDI1
PhD Student, ISISE, University of Minho, Guimaraes, Portugal
farhad.akhoundi@civil.uminho.pt

Graça VASCONCELOS
Assistant Professor, ISISE, University of Minho, Department of Civil Engineering, Portugal
graca@civil.uminho.pt

Paulo B. LOURENÇO
Professor, ISISE, University of Minho, Department of Civil Engineering, Portugal
pbl@civil.uminho.pt

Carlos PALHA
Engineer, University of Minho, Department of Civil Engineering, Portugal
cpalha@civil.uminho.pt

Andreia MARTINS
PhD Student, ISISE, University of Minho, Guimaraes, Portugal

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ABSTRACT

In order to investigate the out-of-plane behaviour of masonry infill walls, quasi-static testing was performed on a masonry infill walls 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. The effect of the distance between thereaction frame of the airbag and the masonry infill on the effective contact area was previously analysed. Four load cells were attached to the reaction frame to measure the out-of-plane force.The effective contact area of the airbag was calculated by dividing the load measured in loadcells by the pressure inside 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.

Deformation and crack patterns 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 but the failure of that interface which 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 trough a well-defined path and the consequent collapse of the infill.

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 behaviour of the buildings. Its presence could have positive or negative effect on the behaviour 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.

Figure 1.Negative effects of infill within structure; soft storey mechanism, (Kusumastuti 2010)(left), short column mechanism (Guevara and García)(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.The earthquakes such as Mexico City earthquake on 19thof September 1985(Miranda and Bertero 1989), Bhuj earthquake on 26th of January 2001 (Jain, Lettis et al. 2002)and L'Aquila earthquake on 6th April 2009(Braga, Manfredi et al. 2011), highlights the damages developed in the infill walls inrelation 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 2the 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.

Figure 2. Damage in non-structural elements(Braga, Manfredi et al. 2011)

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

Figure 3. Detachment of the leaves in multi leaf walls(Braga, Manfredi et al. 2011)

Different researchers have investigated the out-of-plane behavior of masonry walls(Drysdale and Essawy 1988, Dawe and Seah 1989). In (Drysdale and Essawy 1988) 21 full scale concrete block walls were subjected to uniformly out-of-plane loads applied throuhg airbag. The effect of different boundary conditions and also vertical precompression load were studied. The test was performoed monotonically by increasing the pressure inside airbag.The experimental program of Dawe and Seah (Dawe and Seah 1989)included 9 full scale masonry infilled steel frames that were subjected to uniformly distributed lateral pressure that was applied in small increments. Effect of boundary supports, joint reinforcement, panel thickness and presence of opening were investigated and it was concluded that infill compressive strength, panel dimension, boundary conditions 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.

In (Angel, Abrams et al. 1994), 8 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 untill 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 also depends on the compressive strength of the infill.

A summary of large and reduced scale unreinforced masonry infill testing program is represented in (Henderson, Fricke et al. 2003). 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. (2001)(Calvi and Bolognini 2001), 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.

The effect of different boundary conditions on the out-of-plane behavior of the infilled frames wwas investigated by different researcers (Dafnis, Kolsch et al. 2002, Dazio 2008, Tu, Chuang et al. 2010).Different connections conditionsat the top interface between the infill and the frame were considered: (1) joint completely filled with mortar; (2) jointpartially filled with mortar; (3) joint with horizontal gap of 3 mm due to shrinkage of the fresh mortar and (4) masonry infill with unsupported top.No significant differences in the behaviour of the infills with complete and partially filled top joint have been found, whereas a3 mm horizontal gap in the upper mortar joint caused a clearlymodified behaviour of the specimen. The presence of an initial gap in the top joints increases the relative displacement in the gap causing tilting of the infill panel. Infill panel with unsupported top behaved as cantilever beam.It was also concluded that the presence of opening does not alter specimen’s dynamic behaviour. No local effects at the corners of the openings were investigated.

As mentioned before 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

Purpose and Overview

The experimental program in the present study inclues twosteps; (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 efective contact area; (2) out-of-plane testing ofmasonry infill panel built within the RC frame to invesigate itsout-of-plane behavior. In this test a cyclic procedure was used, considering the displacement at mid hehgit of the walls as the control point for the imposition ofthe loading configuration.

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 ona database of buildings from the building stock from different cities in Portugal(Furtado, Costa et al. 2014). Due to the limitation in the laboratory, it was decided to tests 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 4.

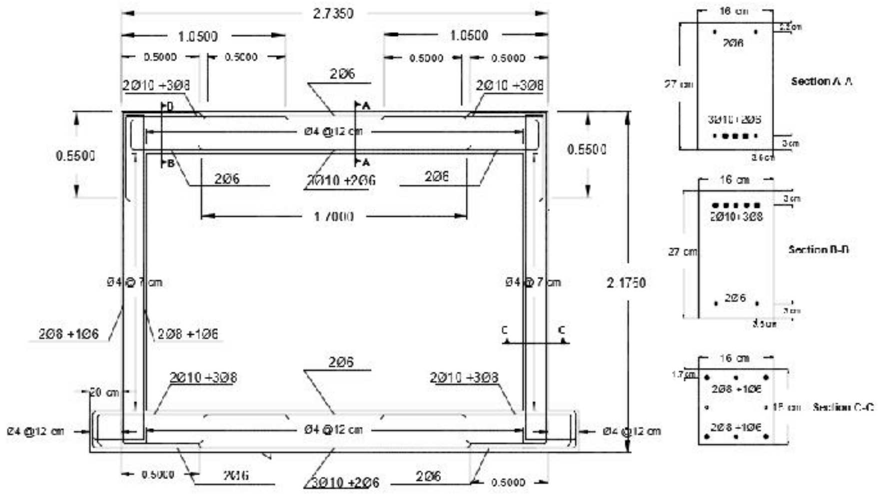

Figure 4. Geometry and reinforcement scheme of the RC frame

This infill masonry panel was constructed with hollow bricks of 30x20x11cm with horizontal perforation, characteristic of the enclosure walls mostly found in Portugal. A M10 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 (EN772-1:2000 , EN1015-11:1999) respectively. The results of the average compressive and flexural strength are represented in Table 1.

Table 1. Compressive and flexural strength of the bricks and mortar used in 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)		10.7
Flexural Strength (MPa)		3.1

Test Setup and Instrumentation

The test setup for the out-of-plane tests of the masonry infill walls is shown in Figure 5. The infilled frame was placed on two separated steel beams that were firmly attached to the strong floor. Sliding of the specimen was prevented by bolting an L-shape steel profile to each side of the steel beam and itsuplifting was also prevented by bolting two rectangular-shape steel profiles to the steel beams. The out-of-plane movement of the enclosure frame was restrained by putting L-shaped steel frame on each side of the upper and bottom beams. Those profiles were bolted to the steel beams. Four 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 testing. The supporting frame of the airbag was in touch with four load cells to measure the out-of-plane load. The configuration of the load cells is shown in Figure 6.

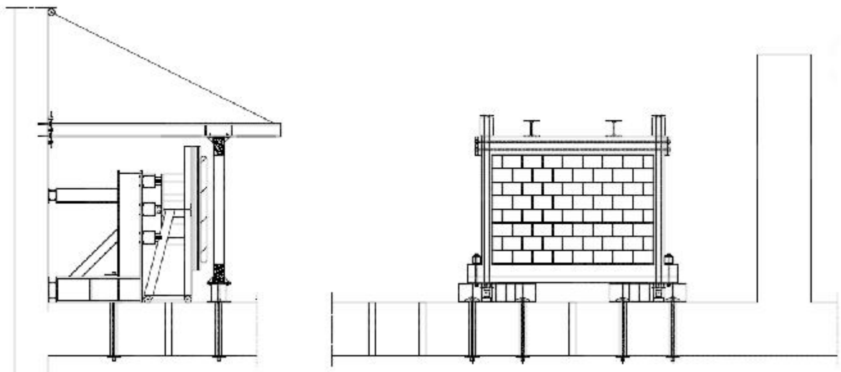

Figure 5. Test setup for out-of-plane testing

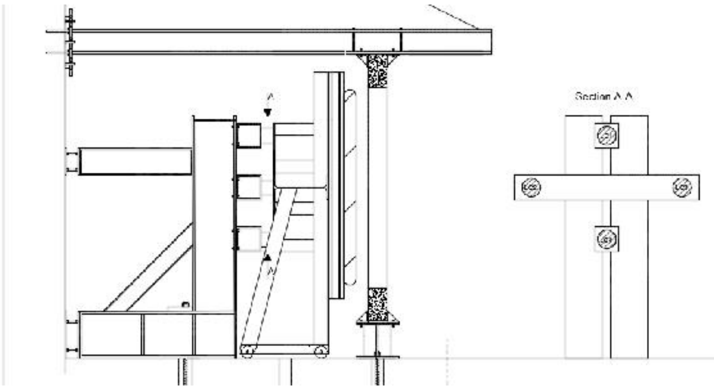

Figure 6.Configuration adopted for the loadcells

The instrumentation plan of the specimen for out-of-plane loading is shown in Figure 7. Fifteen 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.

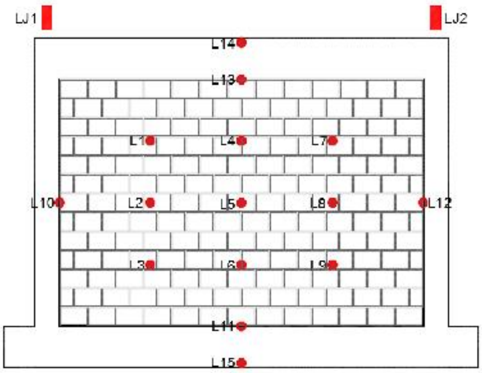

Figure 7. Instrumentation scheme for out-of-plane loading

Two vertical jacks were mounted on the top of each column to apply the vertical load of 80 KN, corresponding to 20% of the column's axial force capacity. Loading protocol for the cyclic quasi-static test of masonry infilled frame was shown in Figure 8. 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 of 2.5mm, 5mm, 7.5mm, 10mm and 21mm. 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.

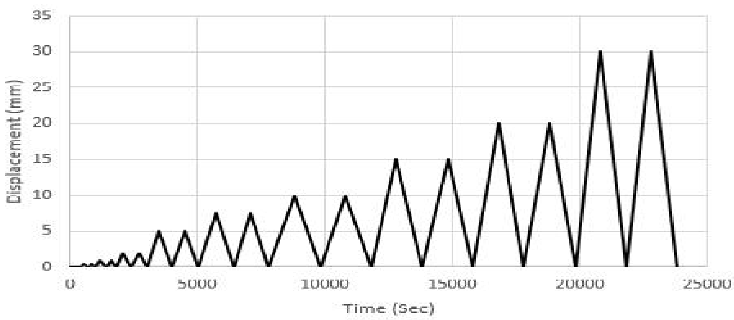

Figure 8. Loading protocol of the out-of-plane testing

Reinforced Concrete Frame with Wooden Board

Wooden board was inserted into a bare frame to studythe 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 15cm, 18cm, 22cm and 28cm were investigated andas it is shown in 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 loadcells. This means that the effective contact area between airbag and wooden board is less that its nominal area. By comparing the results for d=15cm, 18cm and 22cm 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.

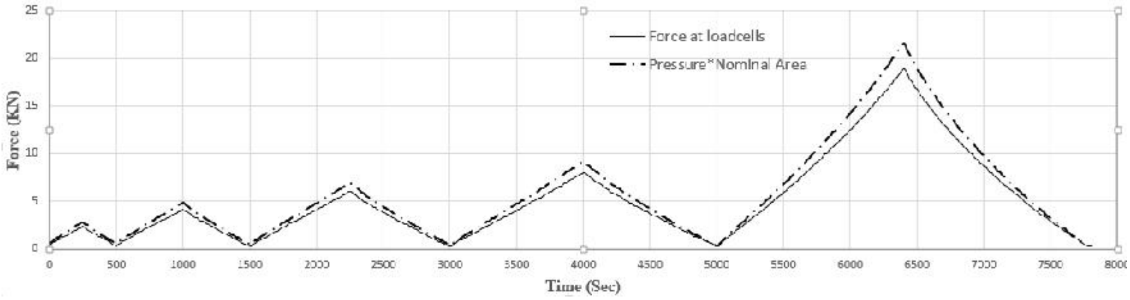

Figure 9. Comparison between the force in the load cells and force calculated by pressure inside airbag for the distance of the airbag of d=28cm

This means that the contact area of the airbag with wooden board reduces by increasing its distance from wooden board, see As it is shown, 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 $R^2 = 0.9891$).

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 15cm to have the effective area equal to nominal area of the airbag. The force-displacement diagram for the control point (mid-point of the infill) is represented in Figure 11.

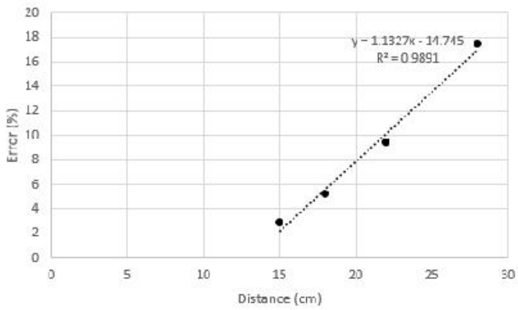

Figure 10. Decrease in effective area of airbag by increasing its distance from wooden board

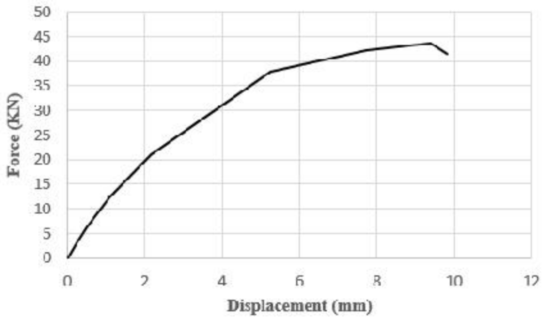

Figure 11. Force-displacement diagram for mid-point of the infill

The out-of-plane load was applied to the infill and until 2mm displacement in the control point there was no visible cracks. By increasing the load at the displacement of 5mm, some visible cracks were observed that were located at the mid-point of the infill in the horizontal direction. At displacement of 7.5mm, the horizontal crack became thick and more visible. At the displacement around 9.8mm the upper interface was crushed and the crack pattern composed of a vertical crack connected to diagonal cracks towards to the bottom corners was observed, see The maximum load corresponding to this failure mechanism was about 45kN.The cracking pattern observed in the brick infill wall is totally compatible with the cracking pattern of the yield line theory of the slabs when the upper interface collapses earlier than the other interfaces. Earlier collapses of the upper interface relates to the construction difficulties of filling the mortar between brick and upper reinforced concrete beam.

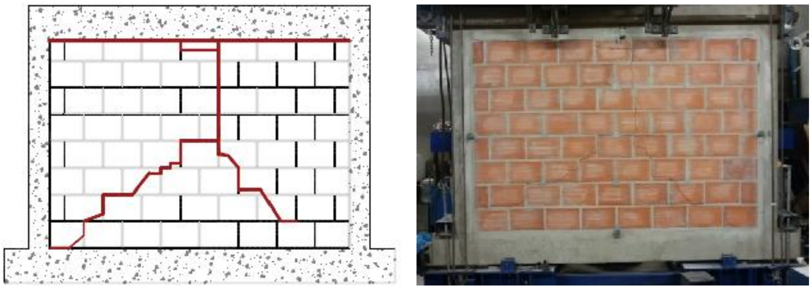

Figure 12. Crack pattern of the infilled frame

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.
- The out-of-plane behaviour of the masonry infill could be assumed as brittle since after the formation of the thin horizontal crack in displacement of 5mm, infill panel suddenly collapses at displacement of 9.8mm.
- 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.

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