EXPERIMENTAL OUT-OF-PLANE BEHAVIOR OF TRADITIONAL BRICK MASONRY INFILL WALLS

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ABSTRACT

The vulnerability of masonry infills within reinforced concrete (rc) frames under out-of-plane loading induced by earthquakes has been observed in several past earthquakes through severe damage and often total collapse. Although the infill panels are assumed as non-structural elements, their damage or collapse is not desirable, given the possible consequences in terms of human life losses and repair or reconstruction costs.

Therefore, it is important to gather better insight on the out-of-plane behavior of existing brick infills so that strengthening guidelines and recommendations can be derived. In this scope, the main objective of this study is to analyze the out-of-plane experimental behavior of brick masonry infilled frames that are characteristic of Portuguese reinforced concrete buildings and that can be seen in other south European countries. In the experimental study carried out, different parameters affecting the out-of-plane response of infilled frames were considered, namely, workmanship, existence of openings and prior in-plane damage. The experimental program was designed to test six half-scale specimens. The out-of-plane loading was applied uniformly to the brick infills by means of an airbag to simulate the effect of earthquakes.

Keywords: Brick infills, out-of-plane test, airbag, force-displacement diagrams, cracking and deformation patterns

INTRODUCTION

The out-of-plane response of infilled frames due to earthquake actions was under scrutiny of different researchers to find out the main influencing parameters. The relevance of studying the out-of-plane behavior of brick infill walls was brought to light in the recent earthquakes occurred in Europe such as L’Aquila earthquake in 2011 [1], where severe damages developed in the infill walls in comparison to some minor cracks observed in the surrounding structure. It was observed that no immediate occupancy was possible due to the generalized damage in the masonry infills. In the examples shown in Figure 1, it is seen that the ground motion was not strong enough to cause structural damage but due to improper anchorage and interaction of the infill walls with surrounding frame, the exterior walls tore away and the concrete beam and columns were exposed. In spite of the out-of-plane behavior of masonry infilled frames have attracted less attention from the research community than masonry infill under in-plane loading, some studies on the out-of-plane behavior of masonry infilled rc frames can be found in literature [2-4].
From experimental analysis, it has been observed that the masonry infill panel surrounded by rc or steel frame can resist significant out-of-plane loads due to formation of arching mechanism [4]. The development of the arching mechanism in the masonry infill is dependent on its confinement by the surrounding frame. When there is no confinement, the out-of-plane resistance is controlled by the rocking resistance along its base.

According to FEMA 356 [5] the formation of arching mechanism is ensured when all the following conditions are satisfied simultaneously: (a) the panel is in full contact with the surrounding frame components; (b) the most flexible frame member presents geometrical and mechanical properties so that the product of the elastic modulus, Ef, times its moment of inertia, If, exceeds a value of 24.82x106 N.mm2; (c) the frame components have sufficient strength to resist thrusts from arching of an infill panel; (d) the height (hinf) to thickness (tinf) ratio of the masonry infill wall is less than or equal to 25. Arching mechanism within the infill may develop in horizontal, vertical or in both horizontal and vertical directions. When only horizontal or vertical arching mechanism develops, it means that the masonry infill has no proper confinement in its horizontal or vertical interfaces respectively. When all the interfaces between infill and frame provide confinement to the infill, both horizontal and vertical arching mechanism develops.

Following the need to better understand the seismic behavior of existing brick masonry infills enclosed in rc frame buildings built in Portugal in the last decades, an experimental campaign was designed to analyze the out-of-plane behavior of traditional brick masonry infills. This paper presents and discusses the experimental results of the experimental campaign. Different parameters that are expected to influence the out-of-plan behavior were considered, namely the workmanship, central openings and previous in-plane damage. It should be mentioned that traditional brick infill walls that were built in recent past decades can be representative of brick infills in other south European countries, which point out also the relevance of the present work.

**EXPERIMENTAL PROGRAM**

In order to investigate the out-of-plane response of brick masonry infills within reinforced concrete rc buildings built in past decades in Portugal (in the 1980s) and that are also representative of brick infills built in other south European countries, an experimental campaign was designed based on static out-of-plane tests. Six reduced-scale specimens were tested in the out-of-plane direction by applying uniform quasi-static out-of-plane loading. As the cavity walls were usually built without any ties between internal and external leaves, there is no interconnection between the leaves. In addition, the outer leaf of the cavity wall collapse much more often when compared to the internal leaf [1]. These reasons justified the application of the out-of-plane loading in the external leaf.

In the experimental campaign, different variables were considered, namely: (a) workmanship quality; (b) presence of openings; (c) previous in-plane damage. The need of a new mason for the construction of the remaining specimens was derived from the poor workmanship used in the construction of one of the specimens. In case of prior in-plane damage, double leaf masonry infills were tested in the in-plane direction until a selected lateral drift. After the in-plane test, the internal leaf was removed and the out-of-plane load was applied only to the external leaf.
The prototype of an rc frame with masonry infills was defined based on a study carried out to characterize typical rc buildings constructed in Portugal since 1960s [6]: (a) rc frame was defined having a length of 4.50m and a height of 2.70m; (b) the cross section of rc columns was 0.3m x 0.3m (length x height) and (c) the cross section of rc beams was 0.3m x 0.5m. The masonry infills were mostly built as cavity walls composed of two leaves with horizontal perforated brick units. The external leaf has mostly a thickness of 15cm and the internal leaf has typically a thickness of 11 cm, being both leaves separated by an air cavity of about 4 cm.

To overcome the space limitation in the laboratory and make handling of specimens easier, reduced-scale specimens were designed following an allowable stress design approach ACI 318-08 [7], adopting a scale factor of 0.54 for all elements. The Cauchy’s similitude law was applied to derive the dimensions of the reduced scale experimental model, see Figure 1. For the masonry infills, horizontally perforated bricks of 175mm x 115mm x 60mm (length x height x thickness) and of 175mm x 115mm x 80mm for internal and external leaves were adopted. The steel used for the construction of rc frame was of class A400NR, with a yielding tensile strength of 400MPa and for the concrete, a C20/35 class was adopted.

![Fig. 1 - Accelerometers placing.](image_url)
Table 1 - Designation of the specimens tested under out-of-plane loading.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Masonry infill</th>
<th>Prior damage</th>
<th>Number of leaves during construction</th>
<th>Mason</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIF-O-1L-A</td>
<td>Solid</td>
<td>None</td>
<td>One leaf</td>
<td>A</td>
</tr>
<tr>
<td>SIF-O-1L-B</td>
<td>Solid</td>
<td>None</td>
<td>One leaf</td>
<td>B</td>
</tr>
<tr>
<td>PIF-O-1L-B</td>
<td>With central opening (12.8%)</td>
<td>None</td>
<td>One leaf</td>
<td>B</td>
</tr>
<tr>
<td>SIF-O(0.3%)-2L(NC)-B</td>
<td>Solid</td>
<td>Prior in-plane damage - drift of 0.3%</td>
<td>Double leaf with no connection</td>
<td>B</td>
</tr>
<tr>
<td>SIF-O(0.5%)-2L(NC)-B</td>
<td>Solid</td>
<td>Prior in-plane damage - drift of 0.5%</td>
<td>Double leaf with no connection</td>
<td>B</td>
</tr>
<tr>
<td>SIF-O(1%)-2L(NC)-B</td>
<td>Solid</td>
<td>Prior in-plane damage - drift of 1%</td>
<td>Double leaf with no connection</td>
<td>B</td>
</tr>
</tbody>
</table>

Three specimens were tested to investigate the out-of-plane response of the brick masonry infills without any initial damage, and also to characterize the influence of the workmanship (specimen SIF-O-1L-A built by mason A, and specimens SIF-O-1L-B built by mason B) and of central opening (PIF-O-1L-B). Three specimens were also tested in the out-of-plane direction, after development of prior in-plane damage corresponding to different in-plane lateral drift levels of 0.3%, 0.5% and 1%. All these specimens were built by mason B.

As leaves of the cavity infill wall are not connected, it was decided to remove the internal leaf and apply the out-of-plane load in the previously damaged external leaf. This enables also to compare directly the results between damaged and non-damaged infill walls.

**Test setup for out-of-plane tests**

The test setup designed for out-of-plane tests is shown in Figure 2 and Figure 3. The bottom beam of the rc frame was attached to two steel beams (HEA300) that were instead attached to the reaction floor in order to avoid any sliding and uplifting.

Fig. 2 - Plan view of the rc frame with brick infill.
Additionally, the sliding of the rc frame with respect to those steel beams of HEA300 was prevented by bolting an L-shape steel profile (L200mm x 200mm x 20mm) to the steel beams, see Figure 2. In turn, the uplifting of the rc frame was prevented by bolting tubular steel profiles (two welded UNP140 steel profiles) to the steel beams.

The out-of-plane movement at the top rc beam was restrained by attaching L-shaped steel profiles (L100mm x 100mm x 10mm) at each side of the upper concrete beam, which instead were bolted to the top steel frame, see Figure 3. Three rollers were placed on the L-shaped profiles to minimize or even eliminate the friction between them and the upper reinforced concrete beam during in-plane loading. To improve the robustness of top boundary restraint under out-of-plane loading, four steel rods M40 were attached to a steel triangular steel structure, connected to two HEB 240 steel profiles that were attached to the lateral reaction wall, see Figure 3.

Two vertical jacks were placed at top of the columns to apply a vertical load of 160 kN, corresponding to 40% of the column’s axial force capacity. Each jack was pinned to the lower steel beam by means of four vertical rods with a diameter of 16 mm (two at each side).

The out-of-plane loading was applied by means of an airbag installed between the masonry infill and a stiff wooden sandwich panel that was attached to a L shape reaction steel structure composed of HEB360 steel profiles. This structure was connected to a L shape steel reaction structure stiffened at the top with a horizontal HEB220 steel profile and with inclined HEB160 steel profile. The stiff wooden sandwich panel is connected to the L shape steel structure by means of four load cells aiming at measuring the force applied by the airbag to the brick infill wall. The configuration of the load cells is presented in Figure 5 (section A-A). Four rollers were added at the bottom part of the stiff wooden sandwich panel to enable its mobility along the horizontal direction without any friction.

**Load history and instrumentation**

The displacement time history adopted in the out-of-plane tests was defined based on the recommendations given in FEMA461 [8], for in-plane tests, see Figure 4. The increment at each stage $i$ was defined as 1.4 times of the displacement at stage $i-1$. The out-of-plane tests were carried out under displacement control, by imposing the required displacement in the central point of the masonry infill (LVDT L5), see Figure 5a. The loading and reloading
procedures were controlled based on Labview software developed for this. Due to the development of plastic deformation in the specimens, the recovery of the total displacement in the unloading branch at the control point was not possible. However, the Labview software was able to invert the cycles once the residual displacement is attained.

The deformation of the brick infill, as well as the cracking propagation, was monitored in the free surface of the wall in front to the surface where the airbag was in contact with. To capture relevant out-of-plane deformations of solid brick infills, fifteen LVDTs were placed on the specimen according to the configuration shown in Figure 5a. (1) LVDTs 1 to 12 enables to define deformation contour levels of the brick infills at different stages of loading; (2) LVDTs 10 to 13 measured the possible detachment of the masonry infill from the surrounding rc frame; (3) two additional LVDTs were placed to record possible out-of-plane movement of bottom and top rc beams (L14 and L15). In case of brick infill with central opening, 16 LVDTs were used to measure out-of-plane deformations during the test, see Figure 5b. In case of this brick infill LVDT L9 was selected to control the out-of-plane test.

![Graph](image)

**Fig. 4 - Load history for out-of-plane tests.**

**RESULTS**

**Force-displacements diagrams**

The force-displacement diagrams obtained for all specimens tested under out-of-plane loading is shown in Figure 6.
Fig. 6 - Force-displacement diagrams of the specimens subjected to out-of-plane loading; (a) SIF-O-1L-A (b) SIF-O-1L-B (c) PIF-O-1L-B (d) SIF-IO(0.3\%)\_2L(NC)-B (e) SIF-IO(0.5\%)\_2L(NC)-B (f) SIF-IO(1\%)\_2L(NC)-B.

From the analysis of the force-displacement diagrams obtained for brick masonry infill walls without previous damage it is observed that: (1) The workmanship influences the out-of-plane behavior of solid brick infills. The response of the brick infill wall built by mason A differs significantly from the response of the brick infill wall built by mason B (SIF-O-1L-B) in
terms of out-of-plane resistance and particularly regarding the ultimate deformation capacity. The brick infill built with mason B presents higher out-of-plane strength and considerably higher ultimate deformation. The post-peak behavior is also much smoother than the post-peak behavior exhibited by brick infill built with mason A (SIF-O-1L-A), which presents a sudden drop in the out-of-plane strength after the peak resistance, revealing also more brittleness. However, in both cases the maximum resistance is achieved gradually after passing the initial linear branch; (2) the brick infill with a central opening (PIF-O-1L-B) exhibit similar out-of-plane strength, when compared to solid infill built by mason B (SIF-O-1L-B), but the deformation capacity is much lower. Besides, the maximum strength is attained for a very low displacement, which results in short pre-peak nonlinear range. It should be noted that the failure of the brick infill with a central opening is brittle. In case of solid brick infills, there is a wide range between the crack initiation and crack development until the ultimate strength is attained.

The out-of-plane behavior of brick infills with prior in-plane damage is characterized by lower stiffness and lower out-of-plane strength when compared to sound brick infill (SIF-O-1L-B). In addition, it is seen that the decrease on the lateral stiffness and out-plane strength is higher for more severe in-plane damage, as expected. In the three specimens with prior damage, the maximum strength is also attained very gradually, being the response of all brick infill walls characterized by a wide pre-peak nonlinear regime. Apart from the lower initial stiffness and strength, the force-displacement diagram of brick infill subjected to in-plane lateral drift equal to 0.3% is rather similar to the behavior exhibited by the sound specimen. The pre-peak regime of brick infills subjected to in-plane lateral drifts equal to 0.5% and 1% is characterized by remarkable change on the stiffness, being the envelop composed mostly of two slopes until the peak strength is attained.

**Cracking and deformation patterns**

The final cracking pattern and deformation scheme of the rc frames with brick infill tested under out-of-plane loading are shown in Figure 7 and Figure 8. It is observed that the cracking patterns are compatible with the deformation of the masonry infills. The low-quality workmanship for masonry infill (SIF-O-1L-A) presents a cracking pattern different from good quality workmanship.

In this specimen, the upper interface sled in the out-of-plane direction due to the inferior filling of the upper mortar joint between the last raw bricks and upper rc beam. This resulted in formation of two-way arching mechanism supported on three sides while in the remaining specimens two-way arching mechanism supported on all sides was observed.

**Fig. 7 - Cracking pattern of the specimens**

a)SIF-O-1L-A b)SIF-O-1L-B c)PIF-O-1L-B d)SIF-IO(0.3%)-2L(NC)-B e)SIF-IO(0.5%)-2L(NC)-B f)SIF-IO(1%)-2L(NC)-B.
In case of specimens with presence of prior in-plane damage, two-way arching mechanism was developed to resist the out-of-plane forces. In the specimen with less prior in-plane damage (SIF-IO(0.3%)-2L(NC)-B), two-way arching mechanism with supports on four sides was developed while in other specimens, due to severe in-plane damage, the upper interface lost its functionality and two-way arching mechanism with supports on three sides was developed. The red lines in the graphs show the cracks that is developed in the in-plane.
direction. Furthermore, it is clear that the presence of minor in-plane damage does not change the total behavior of the arching mechanism since in both cases (SIF-O-1L-B and SIF-IO(0.3%)-2L(NC)-B) the two-way arching mechanism with supports on all sides was formed.

During the out-of-plane tests it is observed that for specimen with minor in-plane damage, the cracking pattern at low levels of out-of-plane loading is affected by the prior in-plane damage, but at higher levels of loading its influence is reduced and new cracks were developed. Inclusively, the cracking observed at the vertical right interface almost did not evolve in the out-of-plane loading.

For specimens with severe in-plane damage (SIF-IO(0.5%)-2L(NC)-B and SIF-IO(1%)-2L(NC)-B), the out-of-plane cracking of the specimens were totally influenced by prior in-plane cracks even in the low or high levels of out-of-plane loading. These demonstrated a lower performance under out-of-plane loading, when compared to the other specimens. In these specimens, the upper interface sled in the out-of-plane direction due to the inferior filling of the upper mortar joint between the last raw bricks and upper rc beam. This resulted in formation of two-way arching mechanism supported on three sides while in the remaining specimens two-way arching mechanism supported on all sides was observed. For a more detailed description of the seismic performance of brick infill under in-plane loading the reader is referred to works carried out by Akhoundi [9] and Akoundi et al. [10].

CONCLUSIONS

This paper presented and discussed the results of an experimental campaign carried out on traditional brick masonry infills of Portugal and other south European countries under out-of-plane loading. The out-of-plane loading was simulated through a distributed load applied with an airbag. Through a simple software Labview routine, it was possible to successfully conduct a controlled cyclic out-of-plane test.

The influence of previous in-plane damage, central openings and workmanship in the out-of-plane behavior of traditional brick masonry infill, namely in the force-displacements diagrams, cracking and deformation patterns was analyzed. From the results obtained, the following conclusion can be drawn:

(1) The workmanship influences the out-of-plane response of the specimens, leading to the reduction of the initial stiffness and out-of-plane resistance. The bad filling of the gap between the upper rc beam and the masonry infill appears to influence the boundary conditions of the masonry infill and consequently the governing resisting mechanism;

(2) The presence of small central opening did not change the out-of-plane resistance of the reference specimen but resulted in a significant reduction of the deformation capacity.

(3) Prior in-plane damage results in decreasing of the out-of-plane initial stiffness and out-of-plane strength. The previous in-plane damage also influences the cracking and deformation patterns, mainly due to the previous in-plane cracks and collapse of the
upper interface between brick infill and rc concrete beam. This led to important
displacement of the top border of the infill at higher levels of out-of-plane loading.

(4) The residual deformation of brick walls, which is more relevant after its cracking,
increases with the progress of damage in the masonry infill.

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