Experimental analysis of brick masonry veneer walls under out-of-plane loading

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ABSTRACT: The evaluation of seismic vulnerability of existing buildings with masonry veneer systems has been recognized as a major problem because of the large number of buildings constructed before the development of rational seismic codes. This resulted in the construction of masonry veneers without reference to the design to seismic action and adequate constructive detailing. In order to contribute to increasing of knowledge about seismic behaviour of brick veneer walls, an experimental campaign was developed on testing quasi-statically full-scale systems under in-plane and out-of-plane loading. This paper describes in detail the out-of-plane performance of a constructive system characteristic of Portugal and South of Europe, constituted of brick masonry veneer leaf connected to an infill wall inserted in a reinforced concrete (rc) frame. A description of the test setup for the out-of-plane tests is provided and the main results, including the damage patterns and force displacement diagrams, are presented and discussed.

1 INTRODUCTION

Brick veneer masonry walls are frequently used as a façade finishing in residential construction in several countries in different parts of the world, namely North America, Australia, England and other European countries due to its aesthetic appearance, durability and its thermal performance. In general, brick veneer walls are separated from an air cavity in relation to a backing system to which it is attached. The backing system can be light wood or steel frames, structural masonry or masonry walls enclosed in rc frames. The backup system is considered as the primary lateral load-resisting system and the brick veneer is considered to be non-structural. The brick veneer walls are attached to the backing system through distinct types of ties, most commonly in steel and can have different shapes and geometry, much dependent on the backing system.

Although the veneer walls are regarded as non-structural elements and are not part of the resisting system of a building, they are subjected to different types of loadings, including self-weight, wind or earthquakes in case of seismic hazard regions. With respect to seismic action, the veneer can be considered as an added mass, neither contributing for the stiffness nor for the resistance.

The performance of veneer walls to loads during seismic events is influenced by the interaction of the veneer with the backup through wall ties, their thickness, height, length, and height to width ratio (Memari et al., 2002). Recent earthquakes occurring in different European countries brought to light fragilities of masonry veneer walls. After many of these events, it was possible to observe common failure mechanisms associated to in-plane diagonal cracking and often the detachment and complete disintegration of the masonry veneer walls. This deficient behaviour should be attributed eventually to the inefficient connections and absence of suitable design rules that consider the effect of the seismic actions on the masonry veneer walls systems (Borchelt, 2004).

Usually, masonry walls present particular vulnerability if pushed horizontally in a direction perpendicular to its plane (out-of-plane loading), but offers higher resistance if pushed along its length (in-plane loading). This is not only valid for loadbearing walls but also for non-structural walls that are forced to behave in a structural way in case of seismic actions. Among the non-structural walls, masonry infills and masonry veneers are well known to be used in more modern construction, where reinforced concrete frames as a structural system predominate.

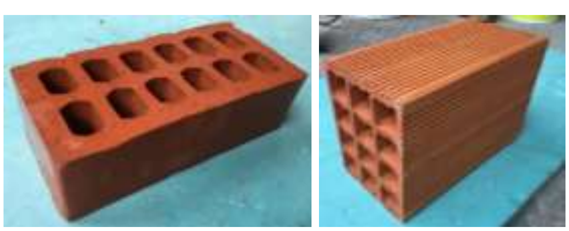
The distribution of the load between the backing support and the brick veneer depends on the type of loading, the stiffness of each element, and the stiffness of the connecting ties. Under wind loads, any in-plane or out-of-lane load in the veneer will to be transferred from the veneers to the backing through the ties. Inertial forces from earthquakes will load both the frame and the veneer. In both cases, the stiffness of the connecting ties should play a key role in the load distribution (Desai and McGinley, 2013).

It is considered that a detailed investigation on the seismic behaviour of masonry veneer walls becomes necessary, especially regarding the connection of the masonry veneers to the backing infill masonry walls. The primary gap identified through literature review was the lack of experimental research that addressed the response of masonry veneer walls, whose backing is composed by masonry infill wall inserted in a rc frame (Martins et al., 2017). This represented the major motivation for conducting this research based on experimental characterization of the mechanical behaviour of brick veneer walls attached to brick masonry infills.

The main results of the experimental campaign intended to achieve are: (1) hysteretic force-displacement diagrams under out-of-plane loading; (2) deformation features of the walls and (3) damage patterns and failure mechanism of the masonry veneers and connections under out-of-plane loading.

2 MATERIALS

The system under evaluation is composed of a rc frame with brick masonry infills attached to a brick masonry veneer by steel ties. The brick masonry veneer wall is constituted by ceramic bricks with vertical holes with approximately 237mm x 115mm x 70mm (length x thickness x height) (Fig. 1a). The brick masonry infill walls were built with ceramic brick units perforated horizontally with approximately 300mm x 150mm x 200mm (length x thickness x height) (Fig. 1b). Notice that, even if the rc frame is built at reduced scale, it was decided to build the brick infill and brick veneer walls with full scale brick units to have better representativeness. The brick veneer walls assemblage was carried out by using a pre-mixed water-repellent cement mortar, usually recommended by the brick unit producer. For the backup, a pre-mixed M5 general purpose mortar was used, following what was used in a previous experimental work carried out on brick infill walls (Akhoundi et al., 2018). The thickness adopted for the mortar bed joints was 15mm to enable the perfect levelling of the tie.



(a) (b)

Figure 1. Brick units; (a) veneer walls; (b) brick infill walls

After a research in the market of steel ties, it was observed that ties with different geometry and shapes are used to attach veneer walls to different backing systems, see Figure 2. Tie wall T6 is composed by basalt fibre and the other ties are made of stainless steel according to technical notes. Apart from the T5 wall tie, the ties are placed on mortar bed joints in infill and veneer leaves, with suitable embedment length.

For the out-of-plane test on the brick veneer wall tested in this work, it was decided to use the steel tie T2. It has a length of 225 mm, a thickness of 5.5mm and a cross section area of 23mm^2.

Figure 2. Wall tie typologies

3 EXPERIMENTAL CAMPAIGN ON MASONRY MATERIALS

3.1 *Brick units*

Six specimens were tested for each brick typology (brick veneer and brick infill) under compression uniaxial loading according to European standard EN 772-1 (2000). The bricks were tested under three different directions (Fig. 3), namely: (a) direction a - parallel to the perforations; (b) direction b – perpendicular to the length of the brick; (c) direction c – perpendicular to the thickness of the bricks.

Figure 3. Loading direction in uniaxial compression of brick units

Regarding the preparation of surfaces, in veneer units, the bed faces of the specimen were cleaned and sanded and any loose grit was removed. For both types of bricks, the surfaces were regularized with levelled thin mortar to achieve an even application of loading. The test machine was a load frame for compression tests with limit capacity of 2500 kN in closed-loop control. The bearing surfaces of testing machine were wiped, and the specimen was aligned carefully in the centre of the ball-seated platen working as an uniform seating. The uniaxial compression testses were caried out in force control with a rate of 2 kN/s. Linear Voltage Displacement Transducers (LDVT) were used in order to record the vertical deformations of specimens during the compressive test.

3.2 *Brick veneer masonry*

The uniaxial compression tests carried out to characterize the compressive behaviour of brick veneer masonry was based on EN 1052-1(1999). The top of the specimens was levelled in order to have a uniform vertical load. The test was performed in displacement control at a rate of 5µm/s. Adequate instrumentation was used so that the stress-strain diagrams and the related mechanical parameters, namely the modulus of elasticity, compressive stress and Poisson coefficient could be obtained.

The flexural tests were based on European standard EN 1052-2 (1999). The flexural strength in pure bending is obtained under four-point loading. There are two typologies of test in order to obtain: (1) the flexural strength with failure parallel to the bed joints (f_{xk1}) and (2) flexural strength with failure perpendicular to the bed joints (f_{xk2}). The specimens support lines were levelled in order to have a uniform load application. The test was performed in displacement control at a rate of 10µm/s. Five LVDTs were used, two at centre of samples (one in front and other at the back), two at loading application points and a LVDT to control the actuator displacement.

4 OUT-OF-PLANE TESTS ON BRICK VENEER WALL

4.1 *Design of masonry specimen*

The experimental model of masonry veneer walls was designed taking into account real features of typical brick masonry veneer walls and laboratory conditions. It was defined based on the constructive system composed of a reinforced concrete (rc) frame with brick masonry infills having attached brick veneer walls. This constructive system is not only very common in Portugal but also in south European countries.

The reinforced concrete frames used in the experimental campaign had been previously used in other experimental campaign on the analysis of the out-of-plane behaviour of masonry infill walls (Akhoundi et al., 2020) (Fig.4). The rc frame could be re-used because the damage previously induced was minor given that the out-of-plane loading was directly applied in the brick masonry infill walls. In addition, fixed bottom and upper beams were considered as boundary condition, resulting in the low damage observed.

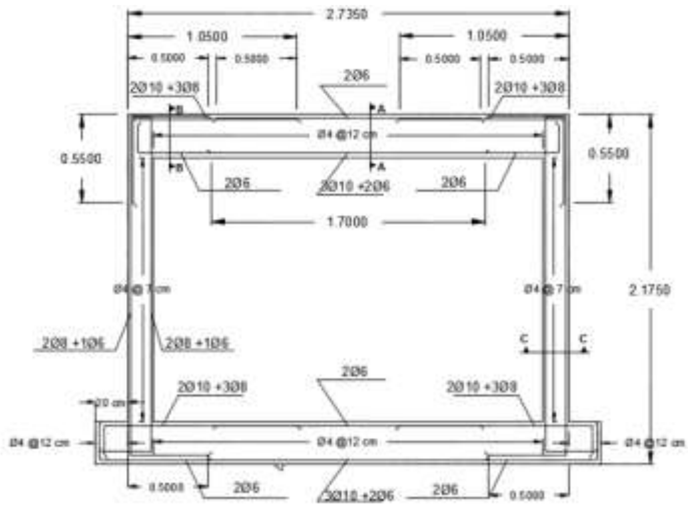


Figure 4. Reinforced concrete frame

The experimental program on brick veneer walls was defined in order to get the maximum information about out-of-plane performance (O) of these constructive elements. The attachment of the brick masonry veneer was carried out by beans of steel ties T2 (Fig. 2) with a spacing of 2.5 ties per meter square embedded in mortar joints. The air cavity distance is 100mm. The interface at the base of the brick veneer was defined by using a flashing system (specimen T2_O_100_2.5).

4.2 *Construction of masonry walls*

The construction of the masonry walls systems (brick masonry infill and brick masonry veneer) is a complex task because it needed be made by phases. In a first phase, the brick infill enclosed in the rc frame was built. In this phase, the positioning of the ties is of major importance to ensure adequate alignment between brick masonry infill and veneer walls (Fig. 5a,b).

After this, a shelf angle is bolted to the bottom rc beam just above the foundation, and a flashing is placed on the shelf angle, as shown in Fig. 5c,d. This was made to evaluate its role in the friction level developed at the base between the shelf angle and the brick veneer. Finally, the brick veneer walls were built parallel to the masonry infill with similar dimensions of the concrete frame (2.32 length x 1.80 height), see Figure 5e,f.

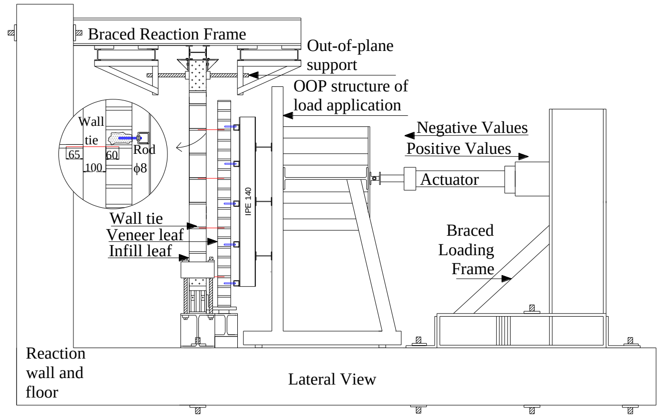
4.3 *Testing setup*

For the out-of-plane cyclic test, a complex solution was designed in order to promote the ideal boundary conditions for the brick veneer walls. The out-of-plane loading/reaction system consisted in three parts (Fig. 6): (1) a braced loading steel frame;

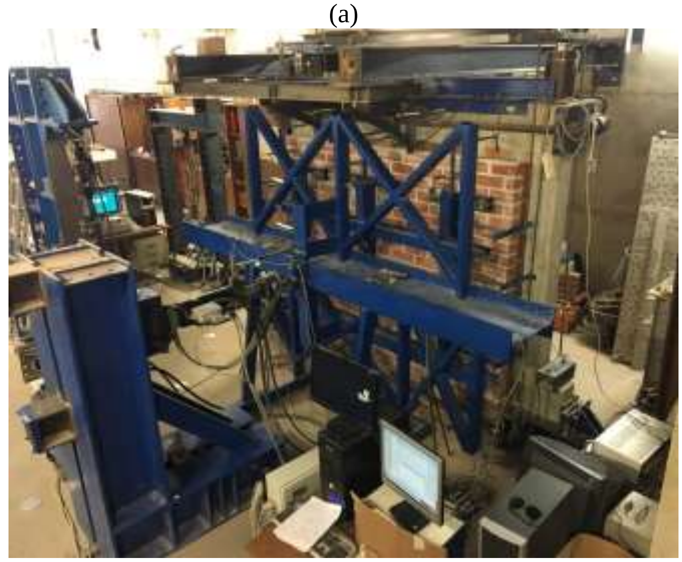
(2) a structure to simulate distributed loading and (3) a steel braced reaction frame. An external steel frame was also placed above the specimens to ensure the restriction of out-of-plane movements at the top beam of rc frame. The restraint was carried out by using four steel rods M40 attached to a steel triangular structure, connected to two HEB 240 steel profiles that were fixed to the lateral reinforced concrete reaction wall. The out-of-plane loading was applied by a structure composed by a welded stiff L-shape profile with a horizontal HEB220 steel profile, an inclined HEB160 steel profile, two perpendicular HEB140 steel profiles and finally a set of tubular elements UNP50.

Figure 5. Construction phases of masonry specimens

Four rollers were added at the base of the steel frame to enable its free movement along the horizontal direction without developing friction and thus to prevent additional forces recorded by the horizontal actuator. This framed structure distributes the load from hydraulic actuator into 30 load points (5 rows and 6 columns). Each load point covers an area of about $0.14 m^2$. The framed structure is connected to the veneer wall trough of threaded rods HIT – V 5.8 anchored to the clay masonry veneer using a Hilti HIT – HY 270 adhesive anchoring system in each load point. As mentioned before, the framed structure is also attached to a horizontal actuator, which in turn is coupled to the braced loading frame anchored to the reaction rc concrete reaction slab. This structure is a rigid HEB360 steel profile fixed adequately to reaction floor to completely prevent its uplifting and sliding during the test.



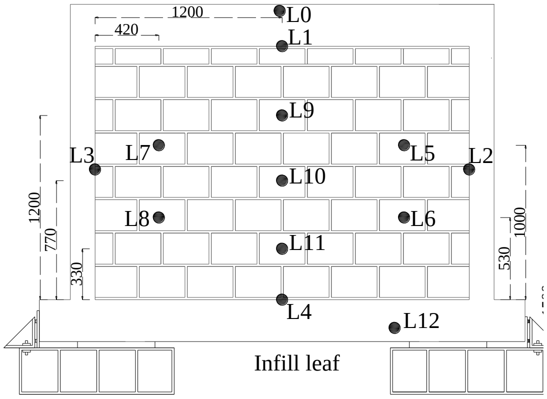
(a)



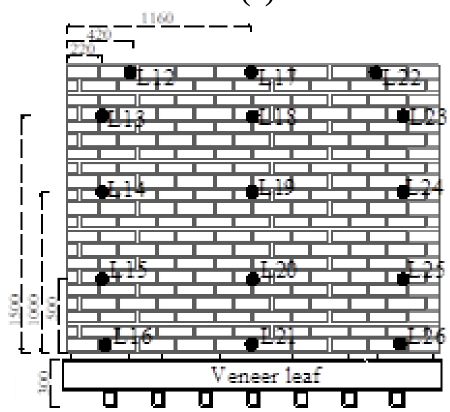
(b)

Figure 6. Test setup; (a) lateral view; (b) frontal view

The instrumentation composed of 31 LVDTs applied both at the infill and veneer brick walls was designed to measure the main deformations, see Figure 7. The out-of-plane deformation of the brick infill was monitored in the back side through 11 LVDTs (Fig. 7a). LVDTs L1 to L4 were applied to measure the relative displacement between masonry infill from the surrounding rc frame. LVDTs L5 to L11 measured the out-of-plane deformation of the infill panel during loading. Two additional LVDTs were placed to measure de out-of-plane movement of the boundaries, namely at the bottom and top rc beams (L0 and L12). In the brick veneer walls, 12 LVDTs were placed according to the layout presented in Figure 7b to measure the main deformations. An additional LVDT was placed on the connection between actuator and structure of load application to compare the internal displacement of the actuator and the real displacement that is imposed to the veneer wall.



(a)



(b)

Figure 7. Instrumentation; (a) infill; (b) brick veneer walls

4.4 *Loading protocol*

The loading protocol was based on FEMA 419 (1997): the displacement amplitude a_{i+1} in step i+1 is 1.2 times the amplitude a_i in step i. All levels are repeated twice, with exception of the first cycle that is repeated six times. The measured displacement law applied at the middle of the remaining brick veneer walls is presented in Figure 8. This law was defined in order to apply increasingly displacements during the out-of-plane test.

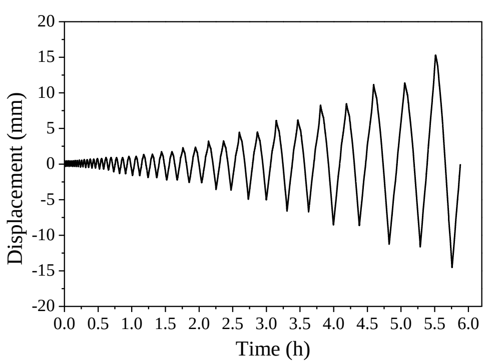


Figure 8. Time displacement history

5 RESULTS

5.1 *Mechanical behavior of masonry materials*

As expected, the brick units present very different values of compressive strength according to the different directions of loading. The normalized compressive strength obtained for masonry veneer bricks was 21.07MPa, 15.97 MPa and 9.04MPa in the loading directions a, b and c respectively. The normalized compressive strength obtained for bricks used in the masonry infill walls was 5.60MPa, 1.45 MPa and 1.47MPa in the loading directions a, b and c respectively.

The stress-strain diagrams obtained in brick masonry veneer wallets under uniaxial compression loading can be seen in Figure 9. Some variation was found in specimen comp_02 sample in terms of maximum resistance and especially in terms of modulus of elasticity. The average value of the compressive strength is about 3.95MPa and the mean elastic modulus is about 8.3GPa. The load-displacement diagrams for each type of flexural test (loading in parallel and perpendicular direction to the bed joints) are presented in Figure 10.

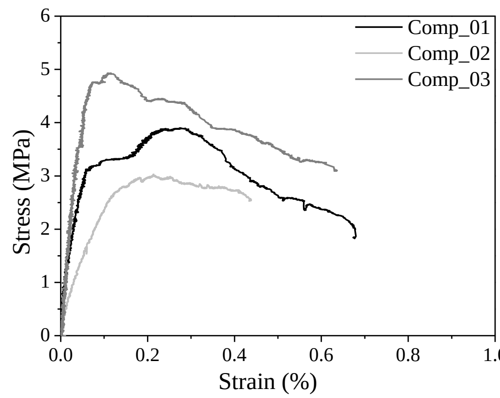
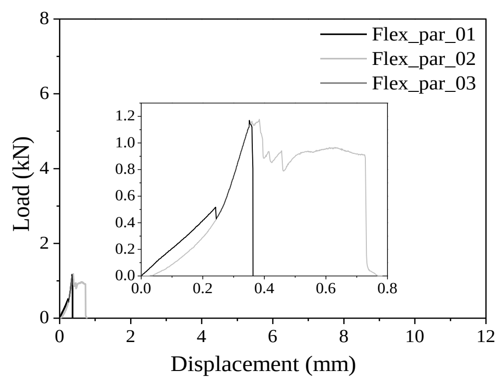
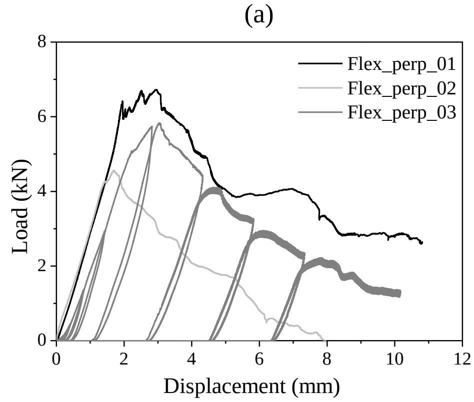


Figure 9. Stress vs strain diagrams



(a)



(b)

Figure 10. Force-displacement diagrams of masonry under flexure; (a) parallel direction to bed joints; (b) perpendicular direction to the bed joints

The stiffness evolution during the cyclic test was assessed in the tests carried out with flexural load according to the perpendicular direction (Fig. 10b). The stiffness is increasing until the maximum resistance is achieved. In the post peak regime, the stiffness is decreasing as expected taking into account the degradation of material and decreasing of resistance capacity. As expected, the flexural strength whose failure is parallel to the bed joints is much lower than the flexural strength in specimens where the failure is perpendicular to the bed joints. The experimental results are comparable to values provided in EC6 (2005) of about 0.1 MPa (f_{xk1}) and 0.4 MPa (f_{xk2}).

5.2 *Out-of-plane behaviour of the brick veneer wall*

The cyclic force-displacement diagrams obtained in the out-of-plane tests for masonry veneer and brick infill walls are presented in Figure 11. For the masonry veneer wall, two force-displacement diagrams are provided, namely considering the out-of-plane displacement measured at the top (L17) and the out-of-plane displacement measured at mid height of the wall (L19). Together to these diagrams, it was also decided to add the force-displacement diagrams of the masonry infill wall (backing wall) considering the displacement measured at the centre of the walls. The idea of representing these different diagrams was to: (1) enable the easy comparison of the deformations between the masonry veneer and masonry infill walls; (2) make the comparison between the displacement at the top and centre of the masonry veneer possible. It should be mentioned that the positive and negative values of force induce tension and compression stresses on ties respectively. Due to these different types of loading, the nonlinear hysteretic response was not completely symmetric because the wall tie has no completely symmetric behaviour under compression and tension loading.

For a better assessment of the performance among the different masonry veneer wall, a comparison between the force obtained experimentally and the force calculated by multiplying the obtained tensile/compression maximum force obtained in single tie-masonry prims assemblages (Martins et al., 2016) by the number of connections considered in the specimen testes under out-of-plane loading. Based on this estimation, it is possible to understand in which extent the resistance of the individual tie-brick connection can be reproduced in the masonry veneer wall.

For the wall under analysis, the experimental maximum load was 29.12kN in the first cycle and 30.6kN in the second cycle in compression. In tension, the maximum force was 26.19kN in the first cycle and 23.18kN in the second cycle. The comparison of these values to the estimated ones enables to conclude that under compression the experimental force was slightly higher than the estimated value, while in tension the experimental and calculated forces are practically the same. The discrepancy between experimental and estimated value can be explained by the workmanship in the application of the wall ties (misalignment in wall ties), differences on boundary conditions of single connections and walls, load application mode and a combination of them. As far is strength concerned, it is observed that a degradation between maximum resistance of first and second cycles.

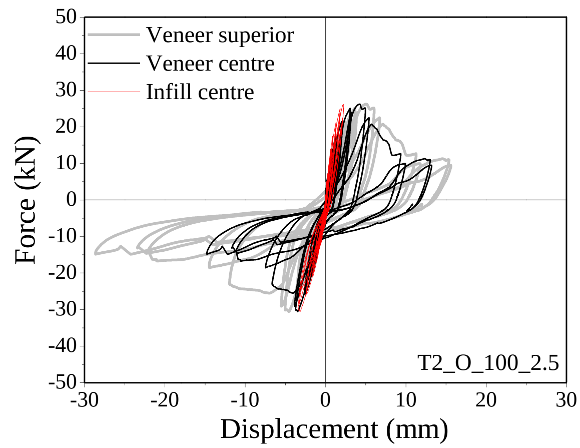


Figure 11. Force-displacement diagrams for infill and veneer walls under out-of-plane loading

A considerable difference between the response at middle and top areas of veneer is noticeable, which is related to the different displacement measured at mid height and at the top. The veneer wall was simply supported at base and anchored through wall ties in its perpendicular direction, being the other three sides free to move in out-of-plane direction, meaning that there is trend for the out-of-plane rotation of the wall, particularly in case of the steel ties are compressed. In both cases the wall rotates, being the base of the veneer working as an “hinge”. Therefore, the wall presents the highest out-of-plane displacement at the top of the wall and the lowest at the base. However, this difference is much more significant when the ties are compressed. This can be explained by the different behaviour of the ties under tension and compression. It was observed that when the veneer wall is pulled and the steel ties are submitted to tension, the veneer wall presents an initial sliding perpendicular to the masonry infill wall and the steel ties are pulled out across mortar joints of veneer and/or infill leaves. When the brick veneer wall is pushed towards the backing system, the steel ties are submitted to compression and due to constrains caused by compression buckling resistance of wall ties, the veneer wall present an evident rotation around the veneer base, being the maximum rotation observed at the top of wall.

As far as force-displacement diagrams of infill walls are concerned, it is noticed that there is a significant difference with respect to veneer wall. The deformation of infill wall is dependent on the capacity that the steel ties have to transfer the out-of-plane loading to the backing system, taking into account that the load is applied directly in the masonry veneer wall. This is a very important aspect to take into account regarding the seismic behaviour because it shows the interaction between both masonry leaves and can provide some indications for a suitable structural design for resisting the loading.

5.3 *Deformation profiles*

The deformation of the brick veneer and masonry infill walls was also analysed. The lateral deformation profile measured at the centre of the walls is provided in order to understand the interaction between the brick veneer walls and brick masonry infill. The sequential deformations of the walls following the cyclic loading are presented in Figure 12. The deformation profiles show the displacements of masonry infill and veneer walls under tension (OOP positive displacement) and compression (OOP negative displacement). Each deformation profile corresponds to the average displacements recorded in the first and second cycle imposed at each displacement level. It is seen that the central profiles of the infill and veneer wall leaves show higher lateral deformation. It should be mentioned that it is common that the displacements of the veneer walls measured by the LVDTs L12-L16 and LVDTS L22 to L26, measure different displacements, meaning that the veneer walls experiments rotation around the central vertical axis.

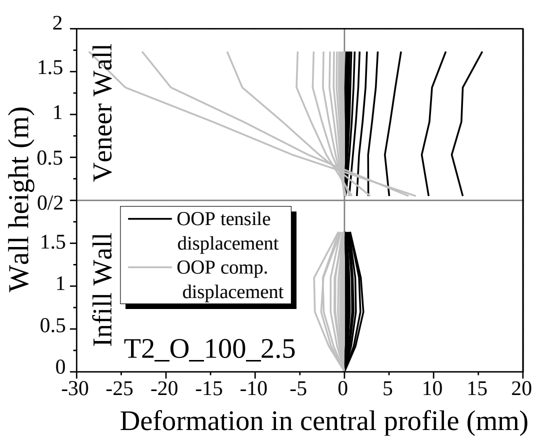


Figure 12. Displacement profiles of infill and veneer walls

For the veneer wall, it was decided to put a strain gauge glued at a steel tie of each row to assess the evolution of strains during the out-of-plane loading. The strains recorded in the steel ties along the central vertical line are provided in Figure 13. In general, it is observed that the strain gauges did not record very high deformations, being usually lower than 2.0‰ but close to the yielding strain. Another important aspect that appears to be relevant is the difference in strains at top and bottom rows of the wall.

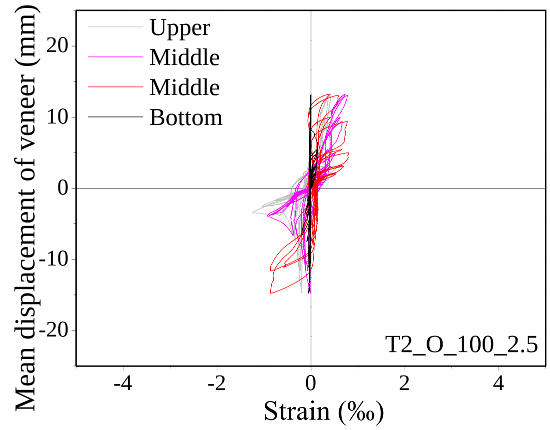


Figure 13. Strains in steel ties along the height of the wall

In all specimens, the values of strain are gradually increasing along the height of wall, being more evident during compression loading. This is mainly related to the higher out-of-plane displacements experienced by the veneer wall, which are mainly controlled by the different boundary conditions at top and bottom borders of the wall.

5.4 *Typical damage pattern*

The distinct deformational features of the walls discussed previously resulted from the different behaviour of the steel ties, namely as regarding the damage patterns both under compression and tension. As mentioned previously, when the steel ties are under compression (veneer walls is pushed), the veneer walls exhibit a deformation mostly characterized by the rotation along a horizontal axis close to the base (rocking), see Figure 12. When the steel ties are working in tension (veneer walls is pulled), the veneer walls also rotate but at much lower grade and mostly slides along the base. When a veneer wall rocks or slides, it can achieve significant displacements without a visible damage. Therefore, the damage is mainly concentrated at the steel ties and at the connection between steel ties and masonry infill and veneer walls. The damages in the steel ties observed consisted of: (1) pull-out of wall tie from embedment bed joint and in more demanding cases the (2) wall tie rupture when veneer wall is subjected to out-of-plane loading under tensile loading.

This justifies the importance these elements in structural safety of buildings with brick veneer walls. The damages on the masonry infill walls are also very reduced, resulting from the low displacements induced by the out-of-plane loads. Notice that the experimental campaign carried out enables to analyse only the out-of-plane loading transfer between brick veneer wall and, thus, the additional out-of-plane deformation induced by an earthquake in case of it has a brick veneer attached.

6 CONCLUSIONS

This paper presents and discusses the experimental results obtained on a quasi-static out-of-plane tests carried out on system composed on an rc frame with brick masonry infill to which a brick veneer walls is attached, The attachment of the brick veneer to the brick masonry infill was carried out by steel ties. The adoption of the rc frame with the masonry infill as the backing system of the brick veneer walls derived from the common use of this structural system in residential buildings in Portugal and in other south European countries.

From the out-of-plane test carried on the brick veneer wall attached to the brick infill wall, it was possible to observed that: (1) nonlinear hysteretic behaviour begins for very early stages of deformation. The hysteretic response is not completely symmetric because the wall ties play a central role on the out-of-plane performance of the system. As steel ties exhibit different behaviour under compression and tension loading, they influence also in the same way the out-of-plane behaviour when tensile and compression loading is induced in the veneer wall; (2) the infill wall develops low deformation levels than the brick veneer and I should be related to the ability of the ties to transfer the out-of-plane loading from the brick veneer walls to the masonry infill wall; (3) the wall ties experienced damages but they were enough to guarantee an adequate post-peak resistance of the veneer wall. The damages observed consisted of: (1) pull-out of wall tie from embedment bed joint and in more demanding cases the (2) wall tie rupture when veneer wall is subjected to out-of-plane loading under tensile loading.

7 ACKLOWLEDGEMENTS

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