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Out-of-plane behavior of brick masonry walls: influence of the tie spacing

Comportamento para fora do plano de paredes de tijolo face à vista: influência os espaçamento dos ligadores

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abstract

In order to contribute to increasing of knowledge about seismic behavior of brick veneer walls, an experimental campaign was developed on brick veneer walls attached to RC infilled frames. This paper describes some results on the out-of-plane performance of a constructive system characteristic of Portugal and South of Europe by considering different tie layout of steel ties.

Keywords: Brick veneer walls, steel ties, experimental analysis out-of-plane behavior

resumo

Com o objetivo de contribuir para o aumento do conhecimento sobre o comportamento sísmico de paredes de alvenaria de tijolo face à vista, foi desenvolvida uma campanha experimental em paredes de alvenaria fixadas a pórticos preenchidos com RC. Este artigo descreve alguns resultados sobre o desempenho fora do plano de um sistema construtivo característico de Portugal e do Sul da Europa, considerando diferentes espaçamentos de ligadores metálicos.

Palavras-chave: Paredes de tijolo face à vista, ligadores metálicos, Análise experimental do comportamento fora do plano

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.

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).

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 pout-of-plane behavior of brick veneer walls.

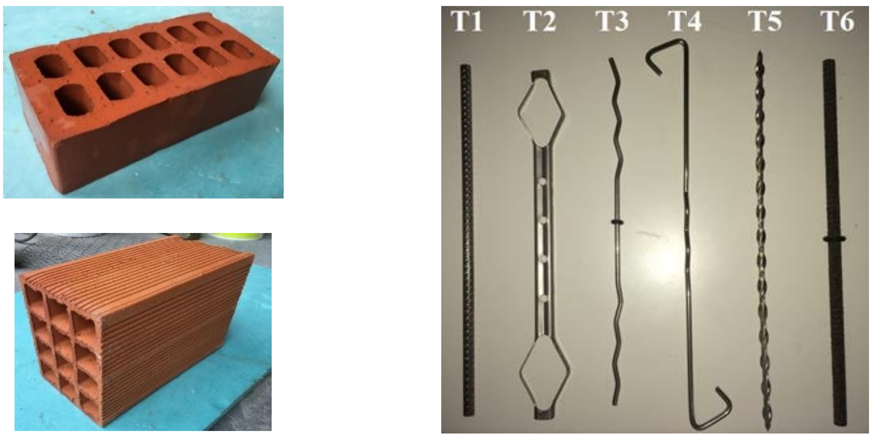
2. DESCRIPTION OF THE EXPERIENTAL MODELS

2.1. Geometry and materials

The experimental models of masonry veneer walls were designed taking into account real features of typical brick masonry veneer walls and laboratory conditions. The experimental model 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 of 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,2016; Akhoundi et al., 2020). 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 the boundary condition, resulting in the low damage observed. The RC frames are considered as typical construction of South European countries in 1980s (Furtado et al., 2014). Given the limitation of the laboratory facilities, it was decided to define a reduced scale experimental model from the representative prototype. For this, a geometrical scale factor of 0.54 was used in the definition of the experimental model. The design of the reinforcing elements of the frame was carried out taken into account the Cauchy's similitude law and the maximum allowable forces and flexural moments of real scale sections obtained according to ACI guidelines (ACI 318-08, 2000). With these guidelines, it was possible to calculate the maximum allowable forces and bending moments of reduced scale cross sections (Akhoundi, 2016).

The brick veneer wall is constituted by ceramic bricks with vertical holes with approximately 237mm x 115mm x 70mm (length x thickness x height). 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), see Fig. 1a. 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 pre-mixed M5 general purpose mortar was used, following what was used in the previous experimental work on brick infill walls. The thickness adopted for the mortar bed joints was 15mm to enable the perfect levelling of the tie.

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 Fig. 1b. 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



(a) (b)

Fig. 1 | Material sued in the experimental model; (a) bricks units for masonry infill and veneer Wall; (2) wall tie typologies and veneer leaves, with suitable embedment length. The wall ties considered in this study were steel ties (T2) selected after an experimental campaign based on tensile-compression cyclic tests on small assemblages composed of the ties attached to brick masonry specimens representing the brick veneer and brick masonry infill walls (Fig. 1b). The steel ties T2 have a length of 225 mm, a thickness of 5.5mm and a cross section area of 23mm².

Construction details and tie spacing

The construction of the masonry walls systems is a complex task because it has to be made by phases. In a first phase, the brick infill enclosed in the RC frame is built. In this phase, the positioning of the ties is of major importance to ensure adequate alignment between masonry and brick veneer walls (Fig. 2a,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 (Fig. 2c,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 Fig. 2e. The air cavity selected for the work was about 100mm, as it is considered a representative value from practice. For this air cavity width, the embedment length of the wall ties on masonry veneer mortar bed joint is 60mm, and in the masonry infill mortar bed joint it is 65mm.

Three wall ties configurations were designed with the aim of understanding the advantage and disadvantages of them in the mechanical behaviour of brick veneers, mainly when submitted to out-of-plane loading. As aforementioned, the location of wall ties in the infill wall was planned so that there was no misalignment of the connectors in relation to the veneer leaf, see Fig. 2f,g In this study, the insulation material in air cavity was not considered.

The ties were applied in the traditional pattern, at an approximately density of 1.4, 2.5 and 5 ties per square meter (Fig. 3). The wall ties configuration is in accordance with the standards that specify this type of element (BS 5628, 1992; TMS 402-08/ACI 530-08/ASCE 5-08, 00, 2008;

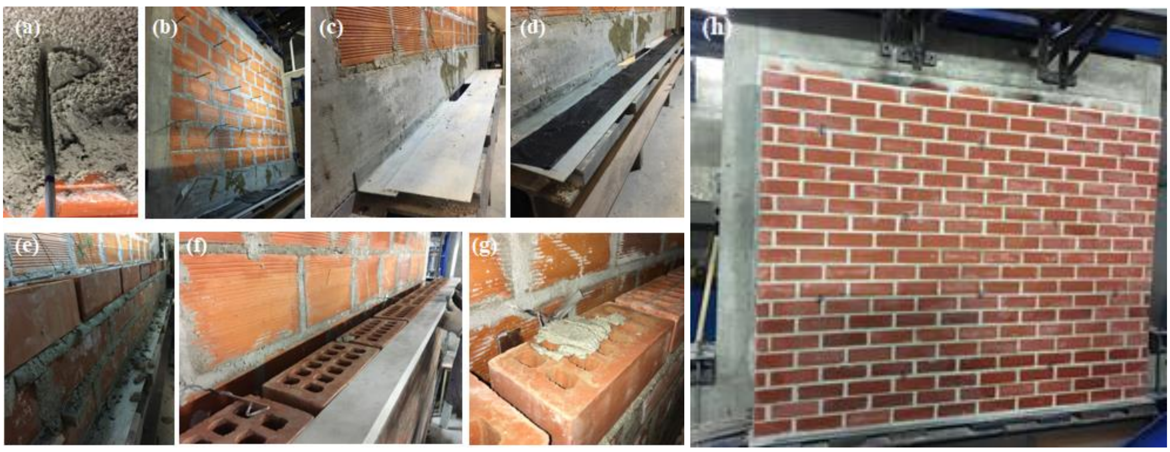


Fig. 2 | Specimen construction detailing: (a) wall tie embedment on infill leaf; (b) previous construction of infill wall; (c) shelf angle without and (d) with flashing; (e) construction of veneer wall; (f) alignment of the connectors and (g) wall tie embedment on veneer leaf (h) global view of specimen

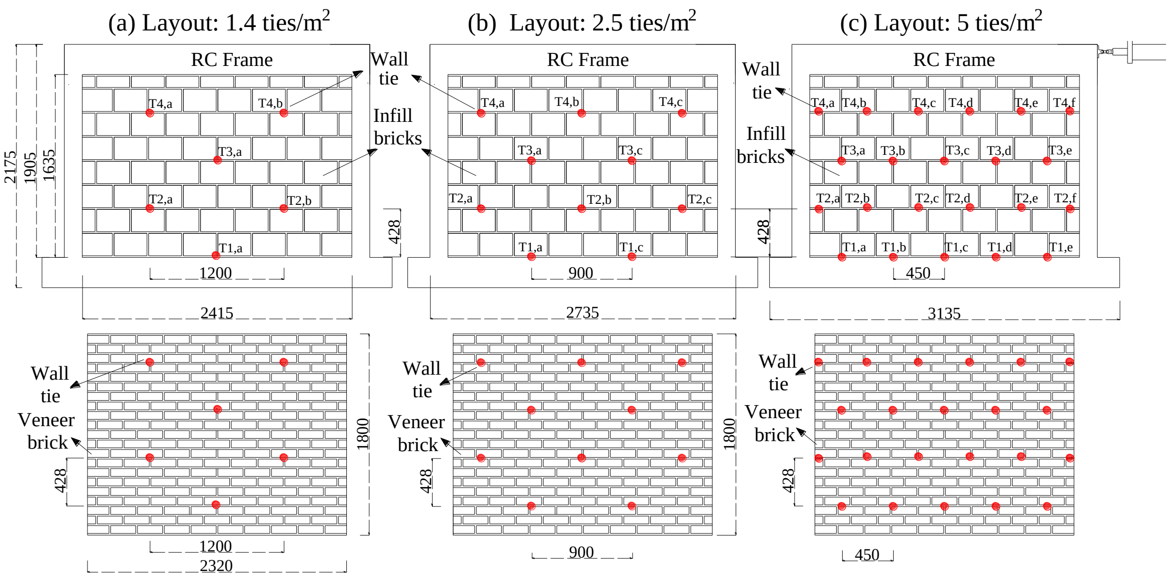


Fig. 3 | Layout of wall ties on masonry infill and veneer wythes (dimensions in millimetres)

AFNOR, NF DTU 20.1 in P1-1, 2008), with exception of greater spacing (1.4ties/m²). This spacing was used with the purpose of knowing the performance of possible current constructive applications, given that it is believed that in practice larger ties spacing should be used. Based on this, three specimens were considered in the experimental campaign according to the tie spacing, namely T2-O_100_1.4, T2-O_100_2.5 and T2-O_100_5, corresponding to a tie spacing of 1.4ties/m², 2.5ties/m² and 5ties/m², respectively.

3. OUT-OF-PLANE TESTS - SETUP AND INSTRUMENTATION

For the out-of-plane cyclic test, a complex solution was designed in order to promote the ideal boundaries conditions for the brick veneer walls. The out-of-plane loading system consisted in three parts: (1) a braced loading frame, (2) a structure to simulate distributed loading and (3) a braced reaction frame (Fig. 4).

The top steel frame was reinforced to ensure that the top beam of RC frame was adequately constrained to out-of-plane movements. 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. 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 induce additional force 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 0.14m². The framed structure is connected to the veneer

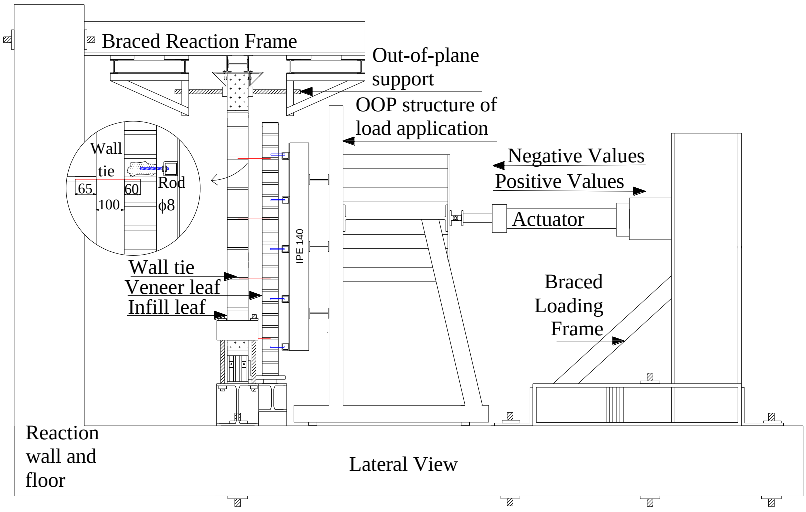


Fig. 4 | Setup scheme for out-of-plane cyclic loading

wall trough of threaded rods HIT – V 5.8 anchored to the clay masonry veneer using the Hilti HIT – HY 270 adhesive anchoring system in each load point. This structure is a steel rigid HEB360 steel profile fixed adequately to reaction floor to completely prevent its uplifting and sliding during the test.

The instrumentation of the infill and veneer brick walls was designed to measure the main deformations was based on 31 LVDTs as shown in **Erro! A origem da referência não foi encontrada.**. The out-of-plane deformation of the brick infill was monitored in the back side through 11 LVDTs. 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 control 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 Fig. 5 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.

Four LVDTs were placed at the external borders of the load application structure to measure the real displacement imposed during test and its distribution on veneer leaf, (L27-L30). The loading protocol was based on FEMA 461 (2007) described previously for the in-plane test:

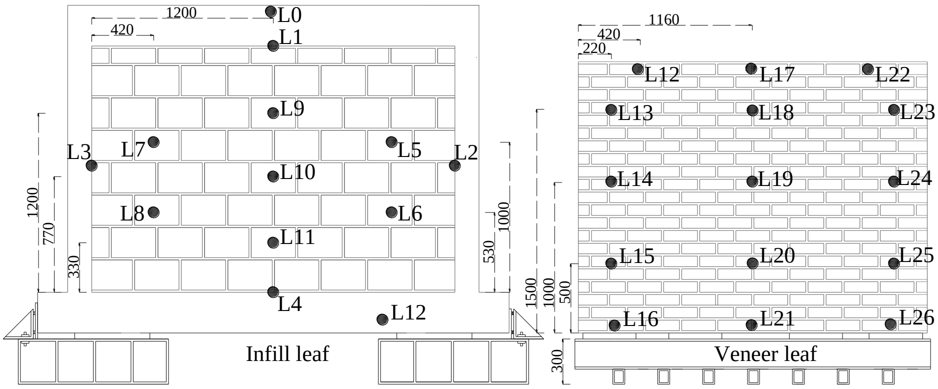


Fig. 5 | Instrumentation scheme for out-of-plane cyclic loading the displacement amplitude a_{i+1} in step i+1 is about 1.2 times the amplitude a_i in step i. The measured displacement law applied for the three specimens of brick veneer walls is presented in Fig. 6. This law was adapted from the first law in order to have more progressive displacements during the test.

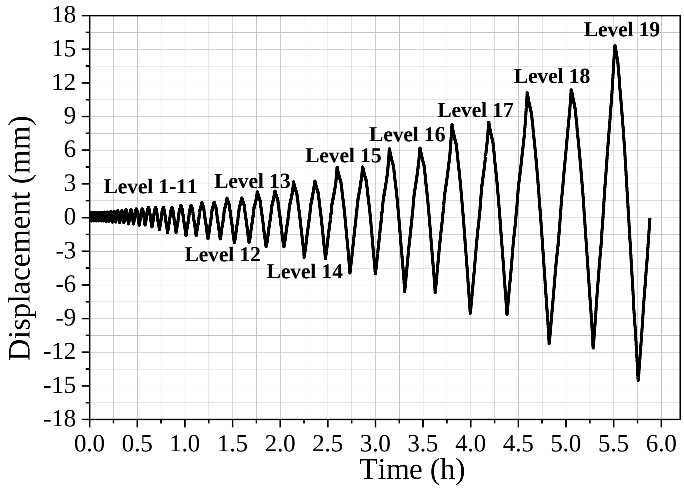
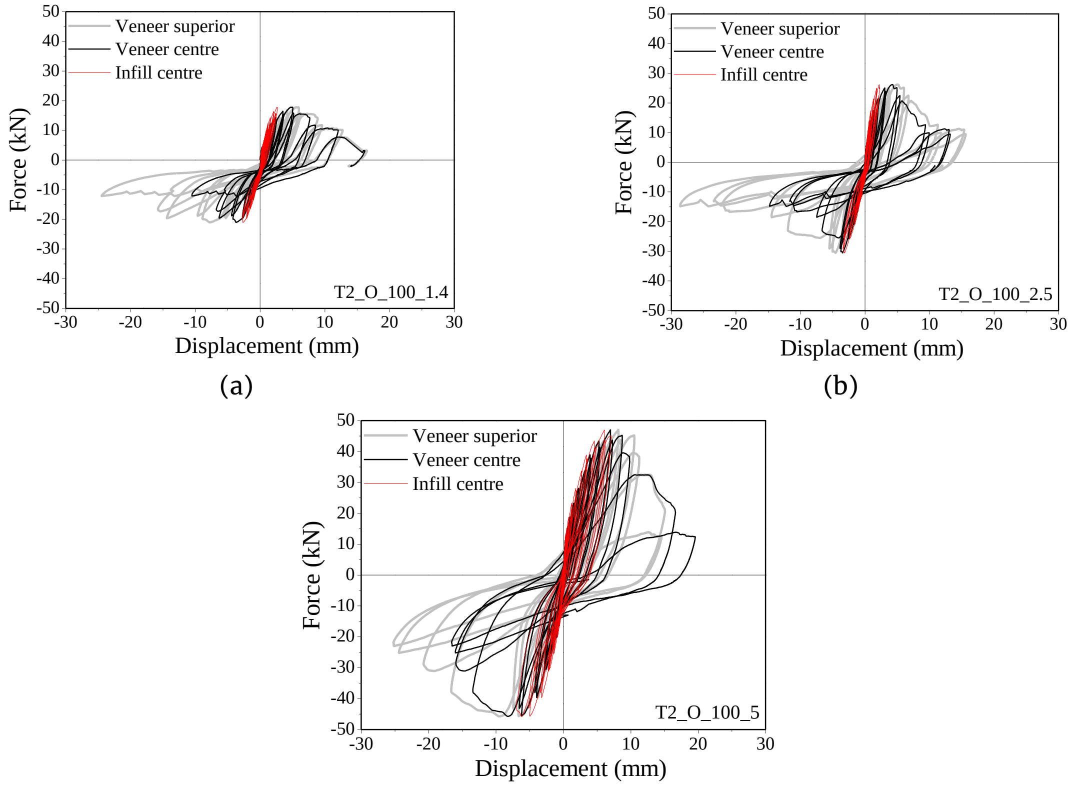


Fig. 6 | Displacement protocol for out-of-plane testing

4. OUT-OF-PLANE TESTS - RESULTS AND DISCUSSION

The cyclic force-displacement diagrams for each specimen are presented in Fig. 7. For the masonry veneer walls, 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 with these diagrams, it was decided also 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 consisted of: (1) making the comparison of the deformations at masonry veneer and masonry infill easier; (2) enabling the comparison between the displacement at the top and centre of the masonry veneer. 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 exactly symmetrical due to the slightly different behaviour of wall ties under tension and compression. The hysteretic curves of walls T2_O_100_1.4/2.5 are slightly flat at the origin, when there is the load inversion, which is associated to the pinching effect. This effect is correlated to the accumulated damage and clearances created, promoted by the contact loss between tie-mortar due to degradation of the connection in successive cycles. As far as concerned to strength degradation between maximum resistance of first and second cycles, it was observed that there was in majority of cases a slight loss of resistance. The average loss of resisting load in tension is higher than in compression loading, being about 8.8% compared with 6% of strength loss in compression.



(c)

Fig. 7 | Hysteretic diagrams

In all walls, a considerable difference between response at middle and top of veneer is noticeable, which is related to the different displacement measured at mid height. Taking into account that the veneer wall is simply supported at base and anchored through wall ties in its perpendicular direction, being the other three sides free to move out-of-plane, there is trend for the out-of-plane rotation of the wall, particularly in case of the wall ties are compressed. In both cases the wall rotates, being the base of the veneer working as an "hinge". Therefore, it presents the highest out-of-plane displacement at the top of the wall and the lowest at the base.

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 wall ties have to transfer the out-of-plane loading to the backing system, taking into account that the load is applied directly in veneer wall. This is a very important aspect to take into account regarding the seismic behaviour because it shows the interaction between leaves and can provide some indications for a suitable structural design for resisting the loading. More deformation of the infill wall means that the wall ties accomplish its function of transferring the load, resulting in the increase of the seismic demand for the masonry infill walls.

The deformation of the brick veneer and masonry infill walls is also analysed in detail (Fig. 8). The lateral deformation profile measured at the centre of wall is provided in order to understand the differences in the deformation pattern among the different walls and understand considering the influence of the type of wall tie and its layout. The deformation profiles are shows the displacements of masonry infill walls and veneer walls under tension (OOP tensile displacement) and compression (OOP compression displacement). Each deformation profile corresponds to the average displacements recorded in the first and second cycle of each imposed displacement level.

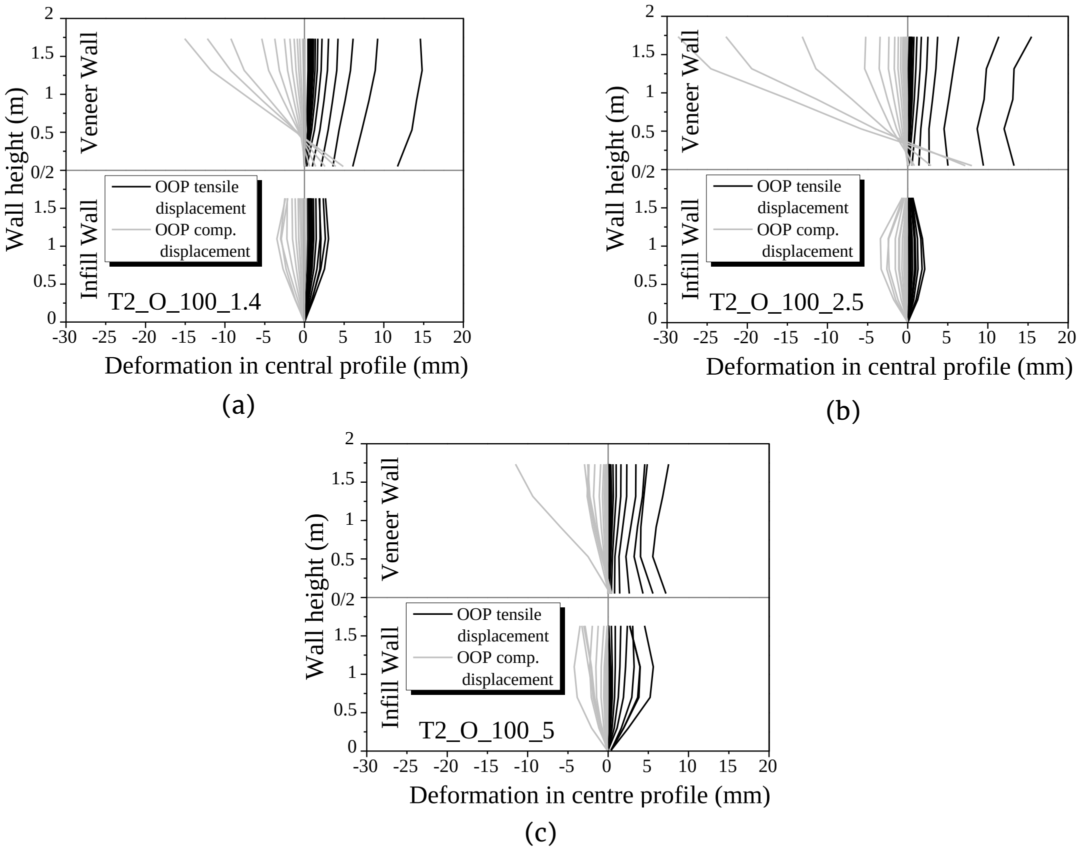


Fig. 8 | Displacement profiles

It is seen that the central profiles of the infill and veneer wall leaves show higher lateral deformation, being represented in the deformation profiles. 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 experiment rotation around the central vertical axis. The displacement profiles along the vertical central line of the masonry walls are clearly different when the walls are submitted to tensile and compression loading. In a first phase, until the attainment of the peak load, the veneer wall did not exhibit great deformations, similarly to what happened in the infill wall. This should be attributed to the composite behaviour associated to the assemblage composed by both masonry walls. After failure of the connections, the stiffness of the system decreases substantially, resulting in the significant increase of the deformation of the walls. In case of the walls are submitted to compression loads, it is seen that horizontal rotation of the walls is more significant when compared to the rotation experienced when the walls are under tensile loading.

4. CONCLUSIONS

This work presented and discussed the experimental results obtained on quasi-static cyclic in-plane and out-of-plane tests carried out on systems composed on an RC frame with brick masonry infill to which a brick veneer walls is attached through different types of wall 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 experimental results it was possible to conclude that: (a) Nonlinear hysteretic behaviour begins for very early stages of deformation. The hysteretic response is not symmetric in majority of cases because the wall ties play a central role on the out-of-plane performance of the system. As they exhibit different behaviour under compression and tension loading, as seen in individual study previously presented, they influence also in the same way the out-of-plane behaviour when tensile and compression loading is induced; (b) The maximum out-of-plane resistance was recorded in system with higher number of ties (lower spacing) both in case of tie; (c) there is a slight loss of resistance between first and second cycles, being achieved the highest loss about 12% due to cumulative damage; (d) The deformation of infill wall is dependent on the ability of the ties to transfer the out-of-plane loading from the brick veneer walls to the masonry infill wall. More deformation of infill wall means that the wall ties accomplish the loading transfer, resulting in a more dissipative response and improving the performance of the system under cyclic loading.

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