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Out-of-Plane Strengthening of Masonry Infills Using Textile Reinforced Mortar (TRM) Technique

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ABSTRACT
The out-of-plane collapse of masonry infills during seismic actions resulted in human life losses and huge repair or reconstruction costs. These problems will result in disturbance of the operational functions of the buildings. The main scope of this research is to analyze the efficiency of different strengthening techniques based on textile reinforced mortar (TRM) technique and using steel connectors in the out-of-plane direction. To accomplish the objectives, four half-scale specimens were tested under uniform out-of-plane loads applied by an airbag to each mass of the infill cyclically. The performance of the textile reinforced mortar technique by using two different meshes was also evaluated experimentally. Besides the protection of the infill from collapsing and protection of human lives, using TRM technique enhances the out-of-plane response of the specimen but its connection to the infill has to be deeply investigated.

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1. Introduction

The high seismic vulnerability of the masonry infilled frame structures observed during the last decades; Mexico City earthquake in 1985 (Miranda and Bertero 1989), Kocaeli (Turkey) earthquake in 1999 (Elnashai 2000) Bhuj earthquake in 2001 (Jain et al. 2002), L'Aquila earthquake in 2009 (Braga et al. 2011), has promoted research on the techniques and materials to strengthen the masonry infill walls and thus to improve their seismic performance. With this respect, conventional or innovative techniques have been presented as an alternative solution. The advantages and disadvantages of the conventional technique are deeply discussed in (ElGawady, Lestuzzi, and Badoux 2004). Some disadvantages of conventional techniques such as space reduction, addition of heavy mass and consequently changing the dynamic properties of the building as well as corrosion of the steel are some common problems that have resulted in the use of composite materials for strengthening. Contrarily, the advantages of the conventional techniques could be summarized as low cost, low technology, limited added mass and increasing the out-of-plane stability of masonry walls.

In terms of advanced strengthening techniques, composite materials have been receiving large attention from the research community and they have been already applied in real context. Some of the main composite systems adopted in civil engineering for strengthening purposes are as fiber reinforced polymer (FRP), textile reinforced mortar (TRM) and composite reinforced mortar (CRM).

Textile reinforce mortar (TRM) strengthening technique already showed to be very efficient with respect to the improvement of the in-plane capacity of masonry elements (Akhoundi et al. 2018; Farhad, Gra and Paulo 2018; Ferrara et al. 2020; Marcari et al. 2007; Meriggi et al. 2021). Few researchers investigated the out-of-plane behavior of infilled frames even if this type of failure has been often observed during past earthquakes. In the research conducted by Tu et al. (2010), four full scale single-storey infilled frame were tested dynamically on a shaking table. The test results revealed that the masonry panel could sustain considerable out-of-plane loads. It was also concluded that the out-of-plane capacity of the structure can be improved if their boundaries could properly strengthened. Another important factor is the thickness of the panel or its slenderness. The panels with double leaf exhibited much higher strength and stiffness than the specimen with one leaf panel.

In the research carried out by Chen et al. (2012) four infilled frames were tested by applying the out-of-plane load to the top beam. In this research, the CFRP retrofitted specimens exhibited higher out-of-plane strength (on average, 1.8 times) than un-retrofitted specimens.

In spite of many advantages associated with use of FRPs, this retrofitting technique is not problem-free.

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Some of its drawbacks are related to the poor behavior of epoxy resins at high temperatures, relatively high cost of epoxy, non-applicability of FRPs on wet surfaces or at low temperatures and incompatibility of epoxy resins with some substrate materials such as clay. Specific properties of clay such as porosity and roughness, which affects the epoxy-brick bond behavior could inhibit the use of FRP (Papanicolaou et al. 2008).

One possible solution to the above mentioned problems can be the replacement of organic binders with inorganic ones such as cement based mortars. The smeared fibers can be replaced by reinforcing meshes such as textile meshes with different continuous fibers. This results in the textile reinforced mortar technique (TRM). This technique is relatively new (it was started to be used in early 1980s) and has been studied by few researchers (Elsanadedy et al. 2013; Papanicolaou, Triantafillou, and Lekka 2011; Papanicolaou et al. 2008). From the experimental work carried out by Papanicolaou et al. on twelve brick masonry wallets subjected to cyclic out-of-plane loading aiming at investigating the effectiveness of TRM versus FRP and **near surface mounted** (NSM) technique it was concluded that the TRM technique leads to higher strength and displacement at failure than FRP. The authors believe that TRM technique could be a promising solution in seismic retrofitting of structures (Papanicolaou et al. 2008).

The experimental work carried out by Papanicolaou et al. on different masonry wallets subjected to out-of-plane cyclic loading also revealed that TRM enhances the out-of-plane behavior of masonry. For out-of-plane loading, the TRM is more effective than FRP in terms of lateral strength and displacement at failure (Papanicolaou, Triantafillou, and Lekka 2011).

Martins et al. proposed an innovative strengthening technique of TRM on infills by making some bending tests on masonry wallets (Martins et al. 2015). Fifteen wallets of masonry were tested under four-point bending tests; namely three wallets as reference specimen, three specimens retrofitted by commercial glass fibers, three specimen retrofitted by commercial carbon fibers, three specimens retrofitted by optimum developed braided composite rods (BCR) meshes of carbon and three specimens retrofitted by optimum developed BCR meshes of glass fiber. It was concluded that retrofitted specimens provide enhanced behavior in terms of increasing the flexural cracking load and maximum resistance to bending. It was also concluded that the specimens strengthened with manufactured reinforcing meshes of glass fibers with BCRs exhibits higher resistance to bending than other retrofitted specimens. It should be also mentioned that the specimen retrofitted with manufactured meshes of braided composite materials with a core of glass fibers present remarkably better post-peak behavior than the other retrofitted specimen. Finally, the authors recommended that the meshes produced with glass fibers are advantageous in terms of their mechanical behavior and can be custom-designed.

In a recent study carried out by Da Porto et al. the effectiveness of different strengthening solutions for light masonry infills were investigated by testing eight full-scale one-bay one-storey clay masonry infilled frames (Da Porto et al. 2015). In this context the solutions were considered as: (i) special lime-based plaster with geo-polymer binder, (ii) bidirectional composite meshes applied with inorganic materials (TRM), (iii) TRM improved by anchorage of the mesh to the reinforced concrete (RC) frame. The specimens were subjected to the combined in-plane/out-of-plane loading. Cyclic in-plane loading until lateral drift of 1.2% was applied to the specimens and then they were subjected to the out-of-plane loading to be collapsed. It was concluded that using TRM strengthening systems further improve the out-of-plane behavior of infill walls. The specimens strengthened with TRM had out-of-plane capacity on average 3.5 times higher than that of the reference specimen and 30% higher than that of specimens made with the same plasters but without any mesh.

Donnini et al. (2021) investigated the in-plane and out-of-plane behavior of tuff and fired clay brick infills by using commercial textile reinforced mortar technique. The effectiveness of the reinforcement is investigated by performing different tests of uniaxial and diagonal compression and three-point bending test. It is concluded that the retrofitting system improves the in-plane and out-of-plane performance of the infills. In the in-plane direction it resulted in increasing in-plane shear strength and in the out-of-plane direction it significantly increased the out-of-plane bending strength and ductility.

De Risi et al. (2020) conducted out-of-plane testing of masonry infills by testing four full-scale masonry infilled frames. The first specimen was assumed as reference specimen and the remaining specimens were strengthened using three different techniques by application of high ductility or common mortar plaster and fiberglass reinforcing balanced nets with two different connection systems with the surrounding frame. The results showed that significant improvement in the out-of-plane strength of the specimens strengthened with ductile mortar was achieved while only 55% increase was observed in the specimen strengthened with common mortar plaster.

In the research carried out by Furtado, Rodrigues, and Arêde (2021), the effect of using textile reinforced mortar on the out-of-plane behavior of masonry infills was investigated. For this, ten specimens were tested under cantilever flexural loading. It was observed that the textile reinforced mortar technique improved the flexural capacity of the specimens until 3.93 times and the deformation capacity until 2 times.

Koutas et al carried out several studies on the behavior of masonry infilled frames strengthened with textile mortar jackets (Koutas and Bournas 2019; Koutas, Bousias, and Triantafillou 2015; Koutas et al. 2014; Koutas, Triantafillou, and Bousias 2015). In (Koutas et al. 2014), different textile based anchors were tested and it was concluded that if the thickness of the infill is less than the width of the concrete member the spike anchors fail by rupture in their bent part at the interface between masonry and concrete when the tensile forces carried by them are about 20–25% of the uniaxial strength of straight fibers. In the recent study carried out in (Koutas and Bournas 2019), six half-scale, one-story masonry infilled frames were tested under four-point out-of-plane loading to investigate the effectiveness of different parameters on the out-of-plane performance of strengthened specimens with textile reinforced jackets. In the strengthened specimens, no connectors were used and the textile meshes were wrapped around the concrete members. It was concluded that the strengthening technique was highly effective in increasing the out-of-plane resistance of the specimens having the effectiveness factor varied from 3.79 to 5.45 for single-wythe wall specimens and equal to 2.45 in the case of the double-wythe wall specimen. The out-of-plane resistance of the specimen is the maximum out-of-plane force attained.

In this paper the out-of-plane behavior of old masonry infilled frames that are representative of the construction practice in south Europe countries is studied. Based on the seismic vulnerability of these type of structures, strengthening technique using textile meshes is applied to the specimens to understand its contribution to improvement of the out-of-plane behavior and also to the limitation of their collapse and falling. Also based on the architectural limitations in the existing buildings contrary to what is done at other studies, it was only feasible to apply the retrofitting technique on the external surface of the infills in which it was not possible to wrap the textile mesh around the RC frames. With this regards, the retrofitting of the specimens in the experimental campaign is performed on the external face. As unreinforced masonry infill showed high out-of-plane resistance, using textile mortar technique is also improved their behavior by increasing the out-of-plane resistance and stiffness and preventing the falling of materials during testing and the time of collapse in which the retrofitting layer plays the role of cover, preventing its falling in the time of collapse.

2. Experimental program

The experimental program for out-of-plane behavior of strengthened traditional brick masonry infill walls in south European countries was based on static cyclic out-of-plane tests. For this, four brick masonry infilled RC frames were considered. The strengthening of the masonry infilled frames was carried out by adding textile meshes embedded in rendering mortar, so-called textile reinforced mortar (TRM), to the brick masonry infilled frames. In one specimen, the masonry leaves were connected by steel connectors to see how this technique could affect the out-of-plane response of the specimen. The connectors are helical-shaped metal ties that are driven into the pilot holes that drilled before. Taking into account the limited facilities at the laboratory of Civil Engineering at University of Minho, it was decided to design reduced scale specimens based on Cauchy's similitude law and test them according to the loading pattern that complies with FEMA-461 guidelines (FEMA 2007). Details about the prototype walls, the design of the reduced scale specimens, tests setups and loading pattern are represented in the next sections.

2.1. *Characterization of prototype and designing reduced scale specimens*

The prototype of an RC frame with masonry infill was defined based on a study carried out for the characterization of the typical RC buildings constructed in Portugal since 1960s (Furtado et al. 2014). The masonry infills were mostly built as cavity walls composed of two leaves with horizontal perforated brick units. The external leaf has a thickness of 15 cm and the internal leaf has a typical thickness of 11 cm, being separated by an air cavity of about 4 cm.

For designing the reduced-scale specimens, an allowable stress design approach was followed. A scale factor of 0.54 was selected to overcome the limitations in the laboratory facilities and also to perform the scaling of all elements, including the dimensions of the bricks. An overview of the scaled reinforcement scheme of the RC frame and of the cross sections of columns and beams are shown in Figures 1 and 2. For the masonry infills, horizontally perforated bricks of 175 mm×115 mm×60 mm and of 175 mm×115 mm×80 mm were used to have

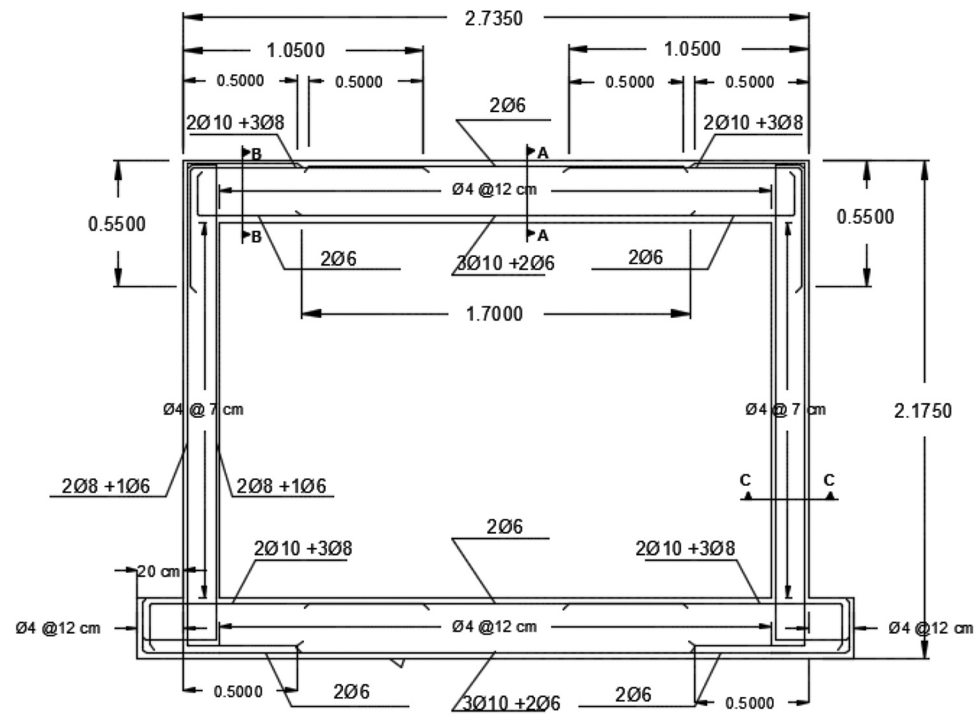

Figure 1. Geometry and reinforcement scheme of the reduced scale RC frame.

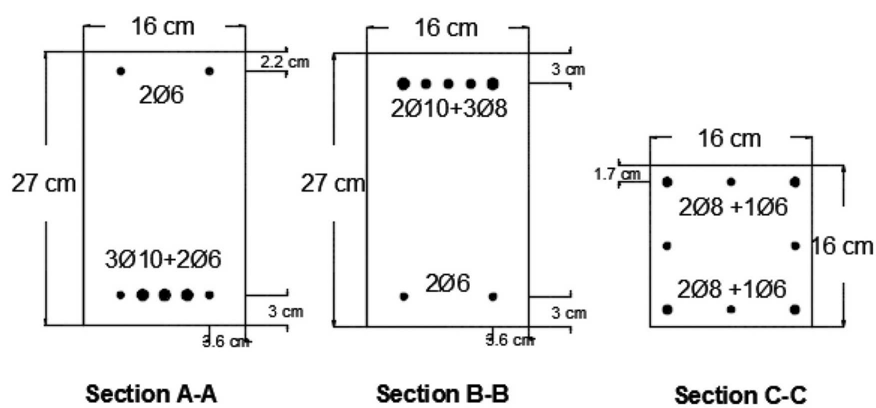

Figure 2. Cross-sections of columns and beams in reduced scale RC frames commercial mesh.

similar height to length ratio of the bricks (0.67) with the one used in the prototype.

In total, four specimens were considered in the experimental campaign, namely one reference specimen (unstrengthened specimen of SIF-O-1 L-B), one strengthened specimen with connection between the leaves (SIF-O-2 L(C)-B) and two strengthened specimens with TRM technique. In the strengthened specimens two different types of reinforcing meshes were used, namely a commercial mesh (specimen SIF(CTRM)-O-1 L-B) and the textile mesh developed in the Department of Civil Engineering of University of Minho (specimen SIF(DTRM)-O-1 L-B) while similar mortar is used for rendering.

The commercial and developed reinforcing meshes used in the strengthened specimens consist of bi-directional glass fiber meshes. The developed mesh is composed of a set of composite rods with an external polyester helicoidally braided with a reinforcing nucleus of glass fibers. The idea is that the braided rod can protect the reinforcing fibers and provide ductility after the rupture of the fibers (Martins et al. 2015), as shown in Figure 3(a). The bond between the external braid and the reinforcing fibers can be ensured in the manufacturing process by adding polyester resin during the braiding process or after the production of the composite braided rods by adding the resin over the external polyester manually (Martins et al. 2015). For the application

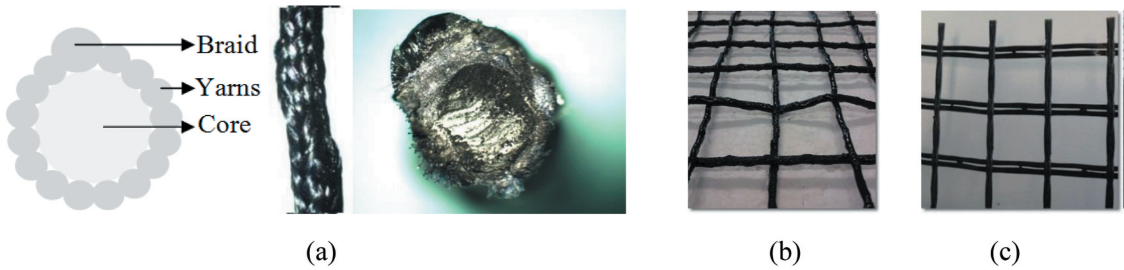

Figure 3. Details of braided rods and meshes; (a) cross section of a braided mesh, (b) designed mesh, (c) commercial mesh.

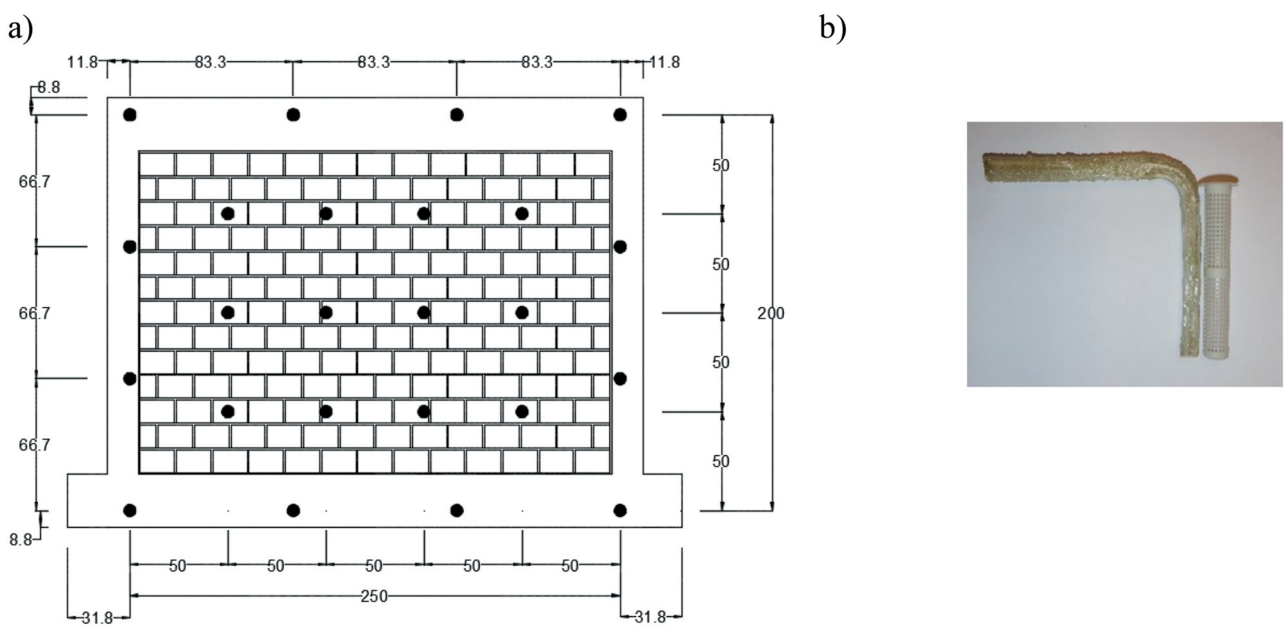

Figure 4. Details of the mesh connectors; (a) pattern of the connectors, (b) plastic row plug and glass fiber connector.

Figure 5. Application of the reinforced rendering; (a) drilling the pilot holes, (b) applying the first layer of mortar, (c) positioning of the textile mesh and application of the second layer of mortar, (d) final aspect after rendering.

on the masonry infills, the composite rod was composed of a braided structure with 15 multifilament of polyester with 11 Tex and one braided element with a simple structure consisting of 8 braided polyester yarns produced at the maximum speed of the production equipment (1.07 m/min). To have manufactured meshes that are comparable with commercial meshes, 5 glass multifilament of the 544 Tex were required, corresponding to a density of 207 g/m2 (about 92% compared to commercial mesh). The manufacturing of the meshes is carried out by interlacing the composite rods in two directions, assuming that the configuration of the connections of rods in two directions may promote an additional interlocking and can work as additional roughness, improving the bond adherence between the meshes and the rendering mortar (see Figure 3(b)).

The commercial mesh consists of resistant glass fibers in both directions as shown in Figure 3(c). The mesh density is 225 g/m2 with spacing between the fibers of 25 mm. As the commercial meshes present a spacing of 25 mm, the manufactured meshes were manufactured with the same spacing.

2.2. Mechanical properties of materials

The mechanical properties obtained in the mechanical characterization of brick masonry include the compressive strength, tensile and shear strength, flexural strength and the mechanical shear properties of the unit-mortar interface.

The compressive strength and the elastic modulus of brick masonry were obtained based on uniaxial compressive loading following the European standard of (EN1052-1 1999). The compressive, shear and flexural strength of the masonry was determined by testing three wallets of masonry with thickness of 75 mm and one wallet of thickness 58 mm. The lower number of specimens of masonry with thickness of 58 mm is related to the smaller number of available units.

An average compressive strength of 1.17 MPa (COV of 4.8%) and an average elastic modulus of 1154.8 MPa (COV of 9.6%) were obtained for the brick specimens representing the external leaf. The compressive strength and the elastic modulus for the brick masonry representing the internal leaf were 1.59 MPa and 1258.6 MPa respectively.

The shear resistance of brick masonry was characterized through diagonal compression tests, following the recommendations of ASTM standard (E519-02 2002). An average shear strength of 0.24 MPa **(COV of 9%)** and shear modulus of 1252.8 MPa **(COV of 1.1%)** were obtained for the brick specimens representing the external leaf. The shear strength and shear modulus for the brick masonry representing the internal leaf were 0.17 MPa and 1017.1 MPa respectively.

The flexural resistance of the brick masonry was obtained in two different directions, namely in directions of parallel and perpendicular to the bed joints according to European standard (EN1052-2 1999). For the external leaf, the average flexural strength of 0.053 MPa (COV of 6.4%) in the direction parallel to the bed joints and of 0.29 MPa (COV of 14%) in the direction perpendicular to the bed joints were obtained. In case of the specimen representative of the internal leaf, the flexural strength in direction parallel to the bed joints was 0.059 MPa, whereas in the direction perpendicular to the bed joints it was calculated as 0.23 MPa.

The in-plane initial shear strength of unit-mortar interface was determined according to the European standard (EN1052-3 2003). Average values of about 0.18 MPa and 0.58 were calculated for the cohesion and tangent of friction angle, calculated through the linear fitting to the experimental results (R2 = 0.87).

The quality of the rendering mortar was controlled by testing the consistency of mortar according to (EN1015-3 2003) in the fresh state and by obtaining the compressive and flexural strength in hardened mortar according to (EN1015-11 1999). The results of the experimental characterization of the rendering mortar used for each type of textile mesh in the specimens are summarized in Table 1.

2.3. Construction and strengthening of the specimens

The construction process of the specimens was divided into two phases, namely casting of the RC frames and construction of the brick masonry infills. The construction of the masonry infills was carried out in the storage area when the frames were placed and after finishing the construction process they were covered to be protected from the rain. After 28 days of curing time for masonry infills, the RC fames with brick masonry infills were carefully transported to the testing place by means of a crane to avoid any cracking.

The rendering mortar used in the strengthened specimens was a pre-mixed commercial mortar indicated to be applied with the selected commercial textile mesh. An additive was added to the pre-mixed mortar aiming at improving its workability and consequently enhancing the mechanical and adhesive characteristics of cement-based rendering mortar. Additionally, L shaped glass fiber connectors were used both in the masonry infill and in the RC frame aiming at avoiding any

Table 1. Consistency, compressive and flexural test results of the specimens.

	Flow table (mm)	Compressive Strength (MPa)	Flexural Strength (MPa)
Rendering with designed mesh	162	9.11 (2.31%)*	3.50 (2.59%)
Rendering with commercial mesh	160	10.44 (4.28%)	3.87 (6.62%)

* Coefficient of variation (COV) has been mentioned inside of brackets.

delamination of the rendering mortar (Figure 4). The application of reinforced rendering to the masonry infills was carried out in the following steps: (i) definition of the pattern for pilot holes (Figure 5(a)) to place the connectors aiming at improving the adherence of the rendering mortar to the masonry infill, (i) drilling and cleaning the holes and insertion of special plastic row plugs shown in Figure 5b in the holes (Figure 5(a)); (iii) application of the first thin layer of mortar (Figure 5(b)); (iv) injecting a special material working as chemical anchor into the holes and inserting the L-shaped glass fiber connectors into them; (v) positioning of the textile mesh on the first layer of mortar; (vi) application of the second layer of mortar and rectifying the rendered surface, (see Figure 5(c) and Figure 5(d))

It is clear that the composite was applied all over the surface covering the RC frame just on the external face. Another technique that can be easily used in existing RC buildings with masonry infills is the one connecting the internal and external leaves so that they can act together under the out-of-plane loading. In Portugal, the tradition of construction in the past decades was based on using double leaf masonry infills (cavity walls). However, there is no tradition in connecting the leaves and it is believed that the great part of the masonry infills built in the last decades are very vulnerable to out-of-plane action due to the earthquake excitations. Therefore, it was decided to evaluate the effect of connecting the leaves of the brick infill with metal ties commonly used in the strengthening of existing masonry infills.

The connectors are helical metal ties that are simply power-driven into position, via a small pilot hole, using a special installation tool that leaves the end of the helical tie recessed below the outer face of the infill to allow an 'invisible' finishing. This is a Dryfix system (provided by Helifix Company), being considered as versatile and rapidly installed mechanical pinning and remedial tying system that requires no resin, grout or mechanical expansion.

It is clear that no chemical bond was used in this technique to fix the helical pins inside the holes, see Figure 6(a). The configuration of the helical ties in the masonry infill is shown in Figure 6(b) using the recommendation of the company.

2.4. Experimental setup, instrumentation and loading protocol

The test setup designed for the static cyclic out-of-plane testing of the RC frames with masonry infills is shown in Figures 7 and 8 in detail.

The instrumentation adopted for the specimens is shown in Figure 9. The instrumentation of the specimen with the leaves connected with steel ties (SIF-O-2 L(C)-B) is similar to the one adopted in the reference specimen (unstrengthened brick infills). In case of the RC frame with brick infill strengthened with TRM technique, additional LVDTs were used to record the possible detachment of the retrofitting layer from the RC frame. For this, three LVDTs were placed on the right side (L13 to L15) of the strengthened mortar layer, three on the left side (L10 to L12), one LVDT at the base of the added layer (L16) and one LVDT at the top part (L17).

The displacement-time history for the control point was defined following the recommendations given in (FEMA461 2007), as shown in Figure 10. Due to the development of plastic deformation in the specimens, the recovery of the total displacement in the unloading branch

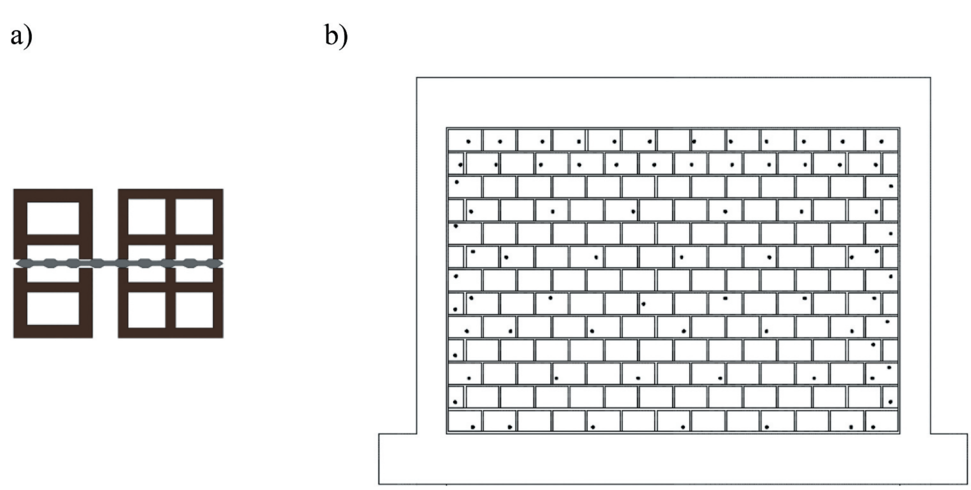

Figure 6. Details of the connections of the leaves through metal ties; (a) metal tie connecting both leaves together, and (b) distribution pattern of helical ties.

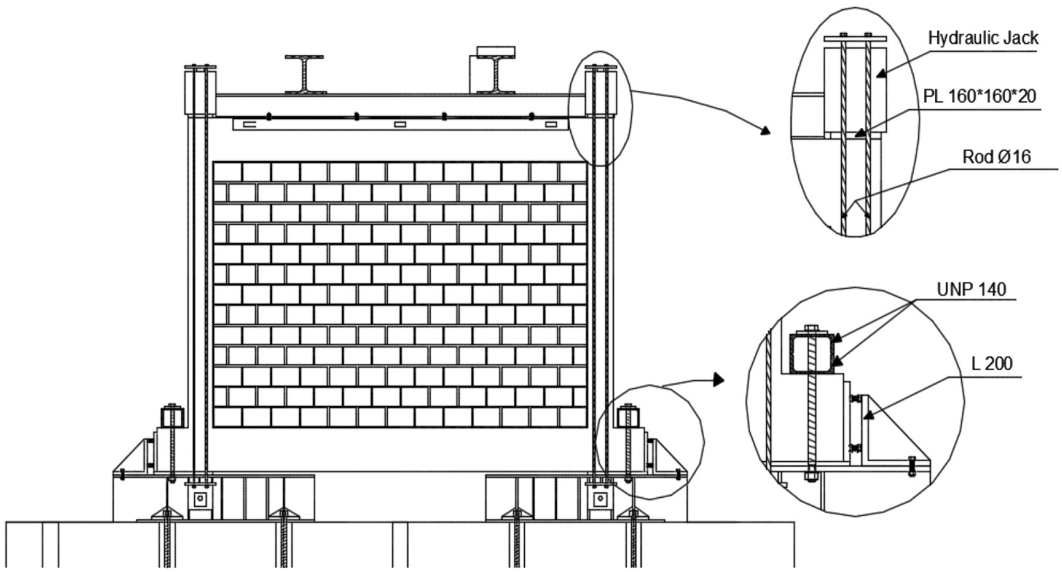

Figure 7. Test setup for out-of-plane testing (front view).

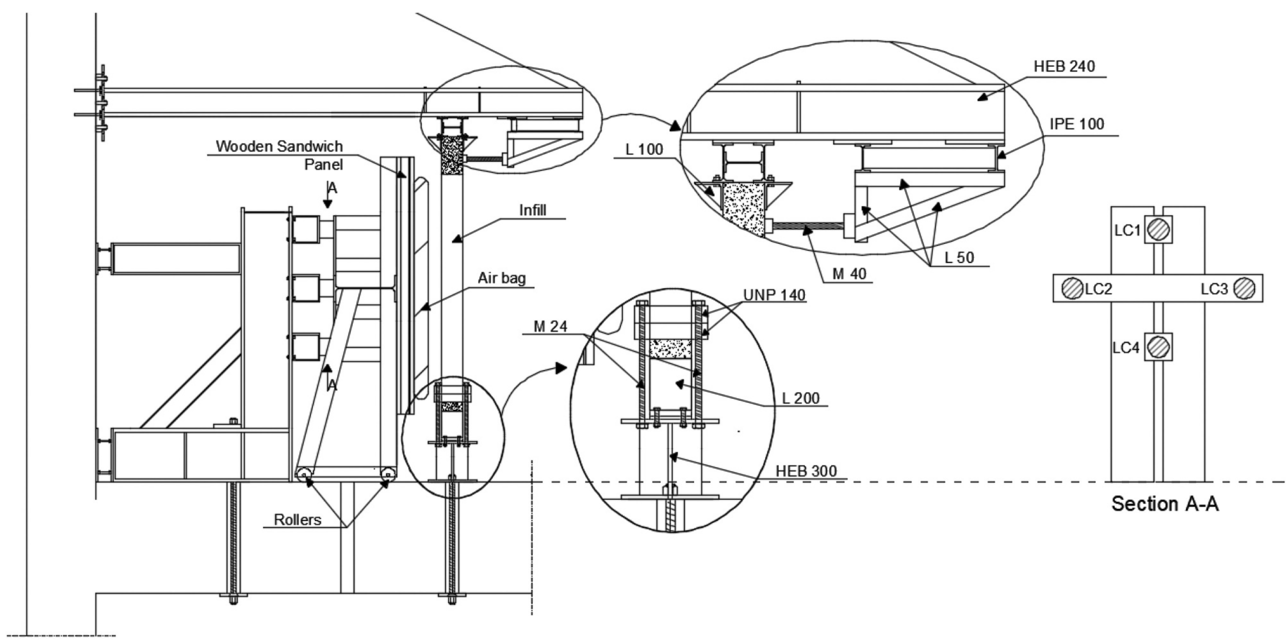

Figure 8. Test setup for out-of-plane testing (side view).

at the control point was not possible. This means that the real minimum displacement in the unloading process was not zero. However, the Labview software was able to invert the cycles once the residual displacement is attained.

3. Experimental results

3.1. Force-displacement diagrams

The out-of-plane response of the specimens are shown in Figure 11. In the specimen where the commercial textile mesh was applied, the steel tubes that support the LVDTs measuring the out-of-plane deformation of the brick infill was fixed directly to the added mortar layer. This resulted in erroneous measuring of the displacements of the brick infill by detaching the added layer from RC frame, even if the masonry infill deformed considerably as seen in Figure 12. After finishing the test, the final deformation of the infill was checked and it was observed that the brick infill was detached from the upper and bottom RC beams. This indicates that the deformation of the masonry was predominantly along the horizontal direction, which should be associated to

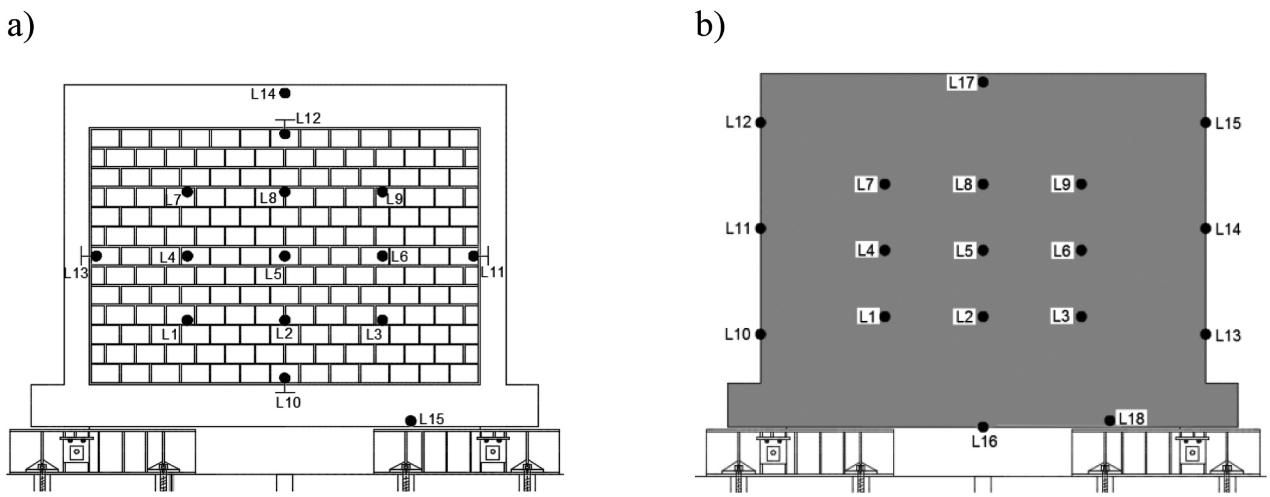

Figure 9. Instrumentation adopted in the out-of-plane testing; (a) SIF-O-2 L(C)-B, (b) specimens strengthened with TRM technique.

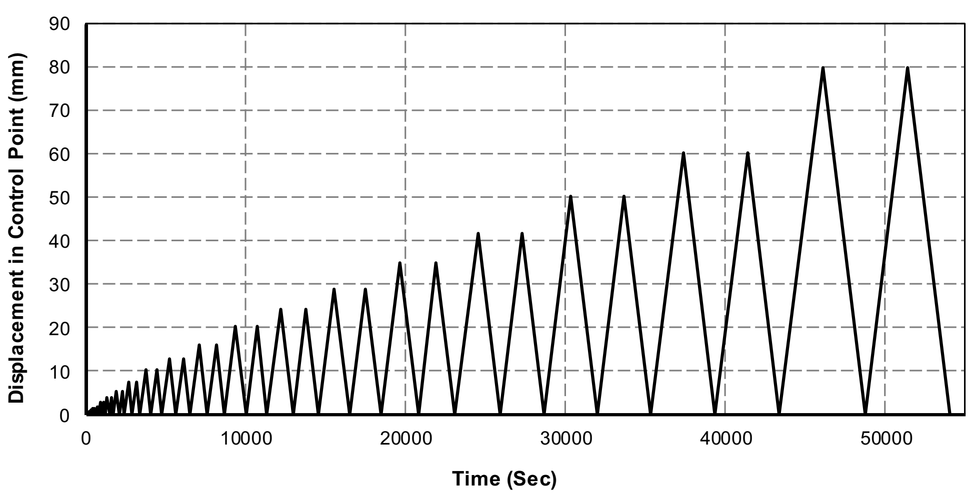

Figure 10. Loading protocol for out-of-plane testing.

the one-way horizontal bending of the masonry infill. The deformation of the wall in relation to its initial configuration was measured, and displacements of about 80 mm and 102 mm were obtained at the bottom and top RC beams. Thus the displacements measured by LVDTs are displacements measured in relation to a movable reference with unknown real displacements. The force-displacement diagram displayed in Figure 11 (c) relates to the real force measured by the load cells and the "relative" displacement measured in the control point (LVDT L5) in relation the points where the steel tubes were fixed.

To overcome the problems encountered in the previous specimen for measuring the exact deformation of the infill, some modifications were made in this specimen for placement of the supports of LVDTs. The supports of the LVDTs measuring the deformation of the infill were directly mounted on the RC beams by cutting the retrofitting layer and fixing to the RC beams as shown in Figure 13. It seems that in this case, the detachment of the retrofitting layer will not cause any problems in the testing program.

Looking at the force-displacement diagrams, it is clear that the maximum out-of-plane force is achieved gradually in all specimens but in strengthened specimens the amount of deformation related to the maximum out-of-plane force is higher; 35.13 mm for retrofitted specimen with TRM technique, 29.1 mm for double leaf specimen and 24.21 mm for reference specimen. It is clear that by connecting the leaves with metal ties, some moderate improvement in the force-displacement diagram is investigated; the maximum

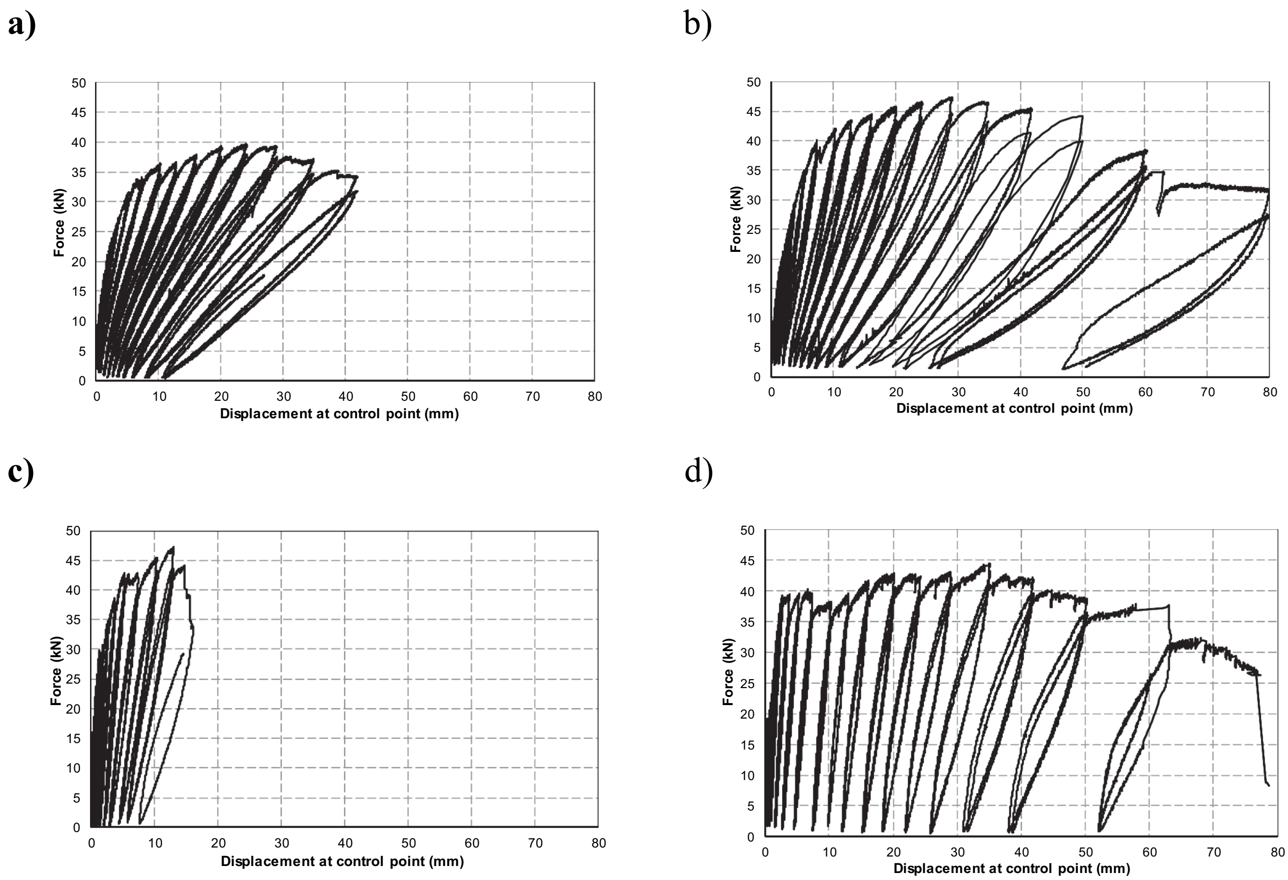

Figure 11. Force-displacement diagram; (a) specimen SIF-O-1 L(B), (b) specimen SIF-O-2 L(C)-B, (c) specimen SIF(CTRM)-O-1 L-B, (d) specimen SIF(DTRM)-O-1 L-B.

Figure 12. Final deformation of the infill.

out-of-plane force, plastic deformation at the end of the cycles and also deformation capacity of the specimen is increased. In this specimen, after the peak force, the reduction in the force is done at lower rates with respect to the reference specimen. It is also investigated that in the TRM retrofitted specimens better improvement in the out-of-plane resistance and deformation capacity is achieved with respect to the specimen with connected leaves.

It is important to notice that there is almost a plateau until the attainment of the out-of-plane resistance in the retrofitted specimen with TRM technique, which appears to indicate that an important redistribution of forces is achieved, which can be associated to a distributed damage. Based on the force-displacement diagram it is seen that the plastic deformations attained very important values, which differentiate its response with the one exhibited by the specimen without reinforced mortar layer. This appears to indicate that the damage is developed in cumulative deformational state of the infill, contrary to what happened in the reference

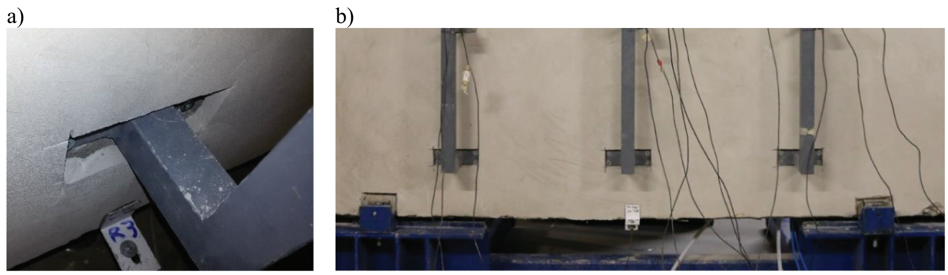

Figure 13. Alternative connection of the LVDTs supports to the RC beams of the frame.

specimens where considerable percentage of the deformation was recovered.

In any case, it should be underlined that the deformation pattern of this specimen should be clearly distinct from the one recorded in the specimens without reinforced mortar layer, as sliding of the brick infill from the bottom RC beam was considerable, contrarily to the reference specimen, where no sliding occurred at the bottom interface. This is also associated to the predominant bending developed in the horizontal direction.

3.2. Crack patterns

The final cracking pattern developed in the cavity walls during the cyclic out-of-plane tests are shown in Figure 14.

Based on the behavior of the specimens by taking into account the results of LVDTs, the reference specimen, deformed in a way that is similar to the deformation of a wall in a two-way arching mechanism. In this pattern, the mid-point of the infill that is assumed as control point, has the maximum out-of-plane deformation. The cracking of this specimen started by formation of a horizontal crack in mid part of the infill and extended to the corners by diagonal cracks which is characteristics of a two-way arching mechanism.

The specimen with leaves connected by steel connectors, deformed in a way similar to what was observed in reference specimen. The mid-point of the infill has the maximum out-of-plane deformation similar to what was observed in two-way arching mechanism. In this case, the formation of the cracks is similar to the reference specimen. In the first stages of loading, the horizontal crack was formed in mid part of the infill and then it was extended to the corners by diagonal cracks.

In the specimen retrofitted by commercial textile meshes, the first cracking is related to a horizontal crack initiating from mid-height of the infill. By increasing the out-of-plane displacement in the control point, the horizontal crack extended and reached the right side

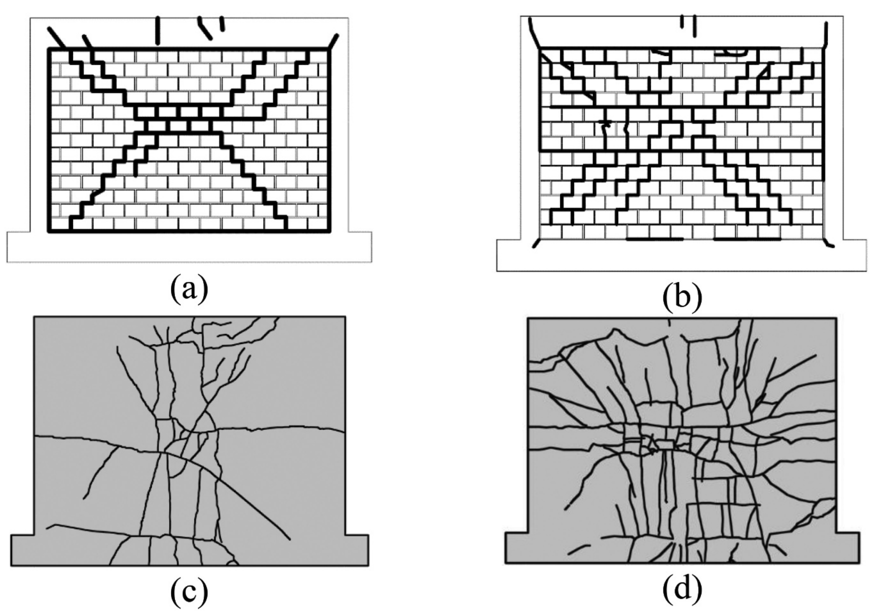

Figure 14. Final cracking pattern of the bare frame; (a) specimen SIF-O-1 L(B), (b) specimen SIF-O-2 L(C)-B, (c) specimen SIF(CTRM)-O-1 L-B, (d) specimen SIF(DTRM)-O-1 L-B.

of the specimen. Looking at deformation pattern and also LVDT recordings, it was concluded that at early stages of deformation the brick infill bended in both vertical and horizontal directions. By further out-of-plane loading, considerable sliding in the upper and bottom interface was observed. Horizontal cracking of the specimen along with considerable sliding of the brick infill through top and bottom RC beams make the predominant flexural bending happens along horizontal direction. The similar pattern of the crack propagation was observed in the specimen retrofitted with developed textile meshes. In this specimen, the first cracking was observed horizontally in the mid height of the specimen. Further loading resulted in development of vertical cracks, connecting the horizontal crack to the top and bottom part of the infill.

The detachment of the reinforced mortar layer from the RC frame was captured at out-of-plane displacement of 3.76 mm at mid height of the right RC column (L14) (see Figure 15) at specimen retrofitted with developed textile mesh. At the displacement of 7.38 mm, the displacement measured in LVDT L16 increased sharply, indicating the detachment of the reinforced mortar layer from the bottom RC beam. The displacement measured by this LVDT continued to increase significantly for subsequent increasing imposed displacements, achieving the value of 10 mm for the lateral displacement of 30 mm. The displacement measured by LVDT L11 was increased for almost 1 mm after the lateral displacement of 7.38 mm. The values of displacement measured by LVDT L11 and L14 are practically the same during the out-of-plane test, indicating the symmetric deformation until the last displacement level. It is clear that the values of displacements are very low, indicating that the detachment of the reinforced mortar layer is very limited, apart from the one observed at the bottom RC beam. Notice that the generalized increasing of displacements measured by the LVDTs placed along the perimeter of the RC frame was only significant at the last out-of-plane displacement levels, corresponding to the collapse of the infill. This appears to indicate the adequate stress transfer from the brick infill to the reinforced mortar layer, resulting in the smeared cracking of the reinforced mortar layer, as previously mentioned.

By combining the information of the horizontal and vertical profiles, captured by different LVDTs, it is concluded that the final deformation appears to be as a result of one-way predominant flexure.

Using the information of LVDTs, it is evident that the control point of the specimen always has the maximum deformation among the other points. It is also observed that at the first levels of loading the specimen deforms symmetrically in the horizontal and vertical directions but at higher imposed displacements, by considerable sliding of infill through the bottom RC beam, the predominant flexural bending could be confirmed as horizontal.

One of the reasons of detachment of the retrofitting layer from RC frame is inefficiency of the connectors applied in the RC frame. The L-shaped connectors were made of glass fibers and were placed on the specimen by means of special resin which were provided by the company that produces the commercial textile meshes. It seems the resin malfunctioned during out-of-plane loading and the connectors slid and finally detached from the RC frame (see Figure 16).

3.3. Comparison of the results

The out-of-plane force-displacement envelopes obtained for the unstrengthened and strengthened brick infills are shown in Figure 17. The parameters

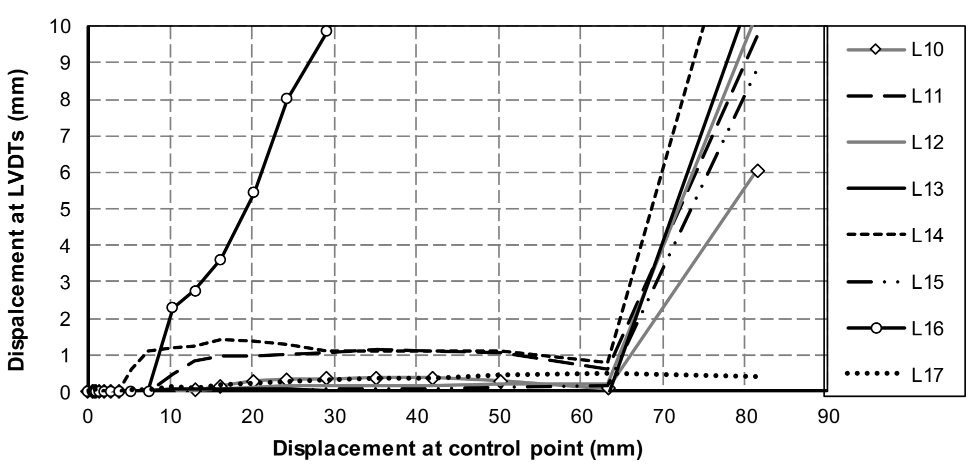

Figure 15. Deformation in LVDTs capturing the detachment between reinforced mortar layer and the RC frame with brick infill.

Figure 16. Detachment of the connectors from RC frame.

related to the initial stiffness, secant stiffness at 30% of the maximum force and out-of-plane resistance of the distinct specimens are represented in Table 2.

It is clear that the consideration of the steel ties to link the internal and external leaves resulted in the increase of the lateral resistance and ultimate deformation capacity. The out-of-plane resistance increased by 18.8% and the initial stiffness increased by 25.6% in relation to the reference specimen of SIF-O-1 L-B.

The addition of a reinforced mortar layer based on textile meshes resulted in the moderate increase of the out-of-plane resistance and significant increase of the initial and secant stiffness. It should be mentioned that it was expected that the out-of-plane strength obtained in the strengthened brick infill could be higher. This could be related to the premature detachment of the retrofitting layer from RC frame which limited the efficiency of this technique for out-of-plane loading.

Looking at force-displacement hysteresis curves of strengthened and unstrengthened specimens in Figure 11, it is observed that in the specimen strengthened with TRM technique, higher plastic deformations could be obtained at the end of each cycle with respect to the reference specimen. This should be associated to the change of the deformation characteristics. In the reference specimen and even in the double leaf brick infill, the resisting mechanism was associated to the two-way arching mechanism. In this mechanism it was possible to observe that part of the deformations were recovered during the unloading process as the majority of the cracks were partially closed. It is believed that the resisting mechanism observed in the strengthened specimens was predominantly horizontal

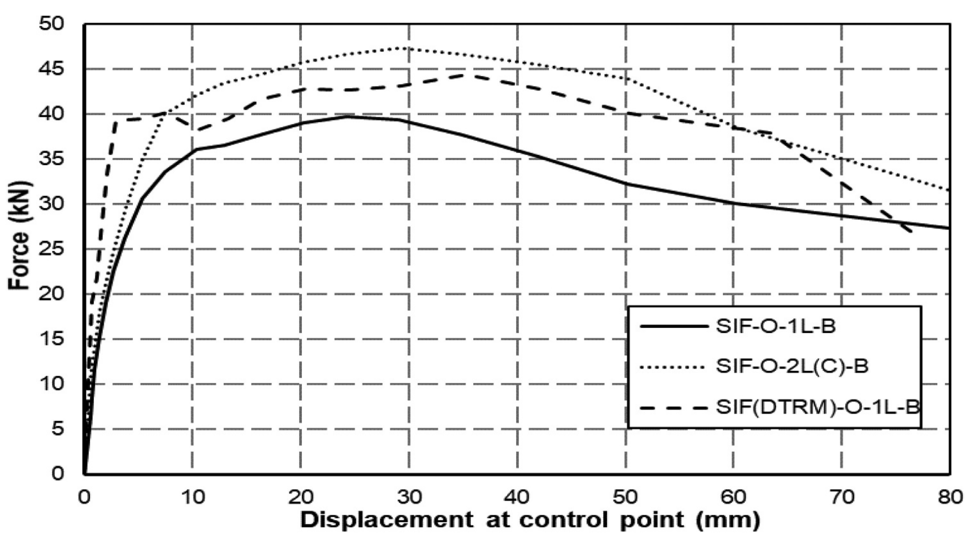

Figure 17. Monotonic envelop obtained in out-of-plane tests.

Table 2. Comparison of the secant stiffness and out-of-plane resistance.

Specimen	Initial stiffness (kN/mm)	Secant Stiffness at 30% of peak force (kN/mm)	Strength (kN)	Increase in initial stiffness (%)*	Increase in secant stiffness (%)*	Increase in strength (%)*
SIF-O-1 L-B (Reference)	12.5	12.5	39.8	-	-	-
SIF-O-2 L(C)-B	15.7	13.2	47.3	25.6	5.6	18.8
SIF(CTRM)-O-1 L-B	-	-	47.2	-	-	18.6
SIF(DTRM)-O-1 L-B	29.3	29.3	44.5	1.3 times	1.3 times	11.8

*Increase with respect to reference specimen

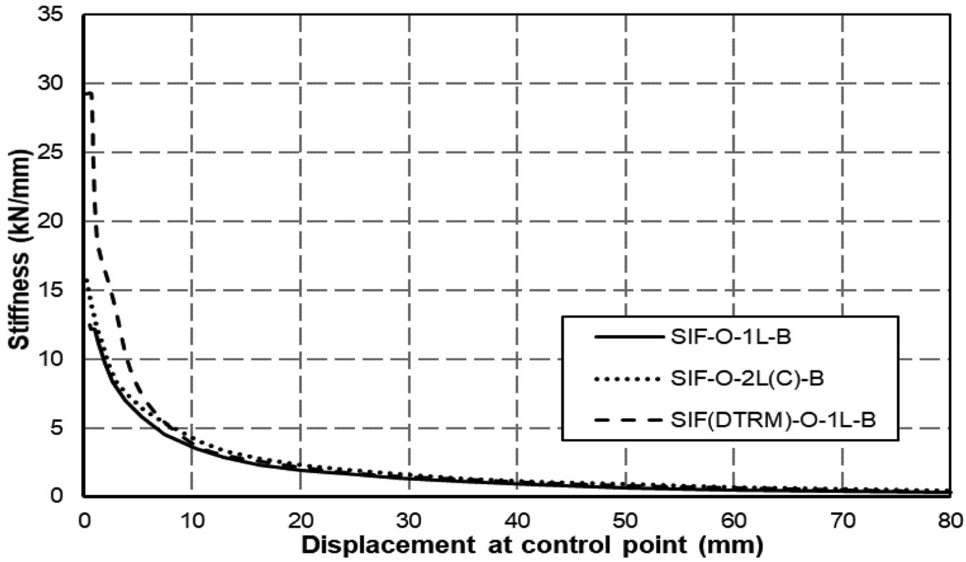

Figure 18. Stiffness degradation curves of strengthened versus reference specimen.

bending of the composite material composed of the brick infill and the reinforced mortar layer where important permanent deformation was developed.

The stiffness degradation curves of the strengthened and reference specimen during out-of-plane loading are shown in Figure 18. It is clear that the strengthened specimens have exhibited higher initial stiffness than the reference specimen. Generally, all the specimens have degraded their initial stiffness at lower displacements but it seems that the degradation rate for specimens with higher initial stiffness is higher. For instance, the strengthened specimen of SIF(DTRM)-O-1 L-B degraded 88% of its initial stiffness at imposed displacement of 10 mm, while the reference specimen (SIF-O-1 L-B) degraded 72% of the initial stiffness until displacement of 10 mm. The value for specimen SIF-O-2 L(C)-B is calculated as 75%.

The total energy dissipation capacity of the strengthened and reference specimens until each cycle is shown in Figure 19. It is observed that the strengthened specimens present higher ability to dissipate energy when compared to the reference specimen. The increase for specimen strengthened with textile reinforced mortar at the end of the test with respect to the reference specimen is calculated as 19%. This value for specimen with double leaves connected by steel ties was calculated as 51%.

Looking at the cracking patterns of the strengthened and reference specimens at the end of the test shown in Figure 14, it is observed that in the specimens strengthened with TRM technique, most of the cracks are concentrated in the added mortar layer and

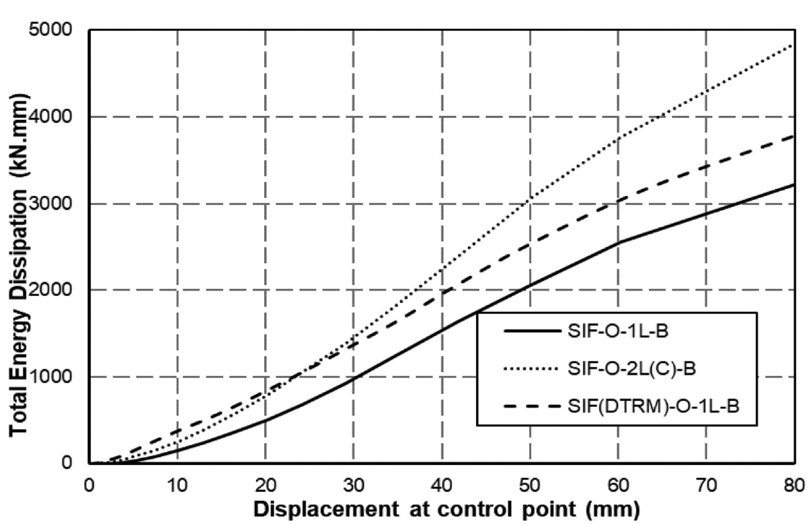

Figure 19. Energy dissipation capacity of strengthened specimens versus reference specimen.

the damage of the brick infill is only associated to the crushing of the bricks adjacent to the upper and bottom interfaces. In this case it seems that the added mortar layer works as damage concentrator and enables us to use this technique as retrofitting technique for damaged infills.

4. Conclusions

Based on the test results of the specimens it could be concluded that;

(1) The TRM technique applied on the brick infill under out-of-plane loading significantly enhances the initial stiffness of the infilled frame, but the increase in the out-of-plane resistance is moderate.
(2) By connecting the exterior and interior leaves of the infill with steel ties, an increase of 25.6% and 18.8% was observed in the initial stiffness and out-of-plane resistance of reference specimen respectively.
(3) It seems that glass fiber shear connectors provided by the commercial company are not effective solutions to prevent the detachment between retrofitting layer and RC frame. In this case based on the results of different research articles, the wrapping of the textile meshes around the concrete members could be investigated for future research.
(4) It is clear that the effectiveness of the retrofitting technique in the out-of-plane direction by using developed textile meshes is similar to commercial meshes which makes the retrofitting process economically custom-designed.
(5) It is clear that TRM technique could significantly increase the residual deformation of the infilled frame, without significant cracking of the brick infill.
(6) The reinforced mortar layer appears to work as damage concentrator when the specimen is subjected to the out-of-plane loading, as the major cracking developed in the rendering mortar.
(7) Specimens strengthened with textile reinforced mortar represented similar energy dissipation capacities in the out-of-plane direction. Besides these specimens have represented higher energy dissipation capacity than the reference specimen.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

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