In-Plane Strengthening of Masonry Infills using TRM Technique

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Abstract

The seismic vulnerability of masonry infills during seismic actions in southern Europe highlighted their urgent need to be studied deeply. Therefore, the main objects of this research are 1) understanding the in-plane behavior of typical south European infilled frames and 2) Providing strengthening technique based on textile reinforced mortar (TRM) technique. To reach the objectives of this study, seven reduced scale specimens were constructed by simulating the same specimens of south European specimens in 1980's. The effect of different parameters was investigated namely; 1) effect of using low strength infills inside bare frame 2) effect of workmanship 3) effect of strengthening technique

Two of them were strengthened by using TRM technique (one were strengthened by using commercial textile mesh and another specimen were strengthened by using the textile meshes that were manufactured in the university. Those specimens were tested under in-plane static cyclic loading to simulate the effect of earthquakes. The loading protocol complies with the guidelines of FEMA 461 [1].

1 Introduction

Masonry infills have been widely used in the building construction as enclosure walls in reinforced concrete (rc) or steel structures for many decades due to their good thermal and acoustic insulation properties and also reasonable fire resistance. Nowadays, masonry infills are still typically used in modern buildings as partition and also as enclosure walls in reinforced concrete frames. Generally, they are assumed as non-structural elements and are not considered in the design of the buildings. Although the infill panels are assumed as non-structural elements, their damage or collapse is not desirable, given the consequences in terms of human life losses and repair or reconstruction costs.

Past earthquakes such as Mexico City earthquake in 1985 [2], Kocaeli (Turkey) earthquake in 1999 [3] Bhuj earthquake in 2001 [4], L'Aquila earthquake in 2009 [5] have confirmed that masonry infills can affect the global and local behavior of the masonry infilled reinforced concrete (rc) or steel frames. In-plane interaction of infill panel with its surrounding frame was studied by different researchers [6-8]. It was concluded that the added infills significantly improve the lateral strength and initial stiffness of the bare frame and also change its dynamic properties [6] [9], which results in a relevant change in the seismic demand of the structure.

The high seismic vulnerability of the masonry infilled frame structures observed during the last decades has promoted research on techniques and materials to strengthen the masonry infill walls and, thus, to improve their seismic performance. With this respect, conventional techniques or innovative materials for in-plane strengthening have been presented. The strengthening can change the behavior of the structure by changing its fundamental period as well as the center of mass and stiffness [10, 11].

Composite materials have been received large attention from the research community and they have been already applied in real context. With this regard, different researchers investigated the effectiveness of using FRPs on enhancing the stiffness, strength and energy dissipation capacity of reference specimens in the in-plane direction [12, 13]. In spite of many advantages associated with use of FRPs, this retrofitting technique is not problem-free. 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 may inhibit the use of FRP [14].

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) which is relatively new (it was started to use in early 1980s) [15-18].

The first studies on TRM technique were almost carried out on concrete specimens. In the research conducted by Triantafillou et al [19] TRM is used as a means of increasing the axial capacity of RC columns through confinement. It was concluded that using TRM jacketing resulted in substantial gain in compressive strength and deformability of the specimens.

Martins et al [20] proposed an innovative reinforcing mesh to be used in the TRM strengthening technique for brick masonry infills. The textile meshes are composed of braided composite rods (BCR) manufactured from a braiding process. Fifteen wallets of masonry strengthened with different commercial textile meshes and with new mesh with braided composite rods were tested under four-point bending tests. It was concluded that the specimens strengthened with manufactured reinforcing meshes of BCRs with carbon fibers exhibit higher resistance to bending than other retrofitted specimens. It should be also mentioned that the specimens retrofitted with manufactured meshes of braided composite materials with a core of glass fibers presented remarkably better post-peak behavior than the other retrofitted specimens.

The results obtained in this research, by using textile meshes that were developed in the University of Minho and also using different type of connectors with respect to [21], revealed that TRM technique enhances the global behavior of the infilled. As internal and external facades of the infill were in line with those of RC beams and columns, it was not possible to connect the textile meshes to the infilled frame by similar technique that was used in [21]. Bases on the results, it seems that glass shear connectors, used in this study, are less effective and needs to be investigated in detail as they failed in shear in connection part of the added mortar and RC frame.

2 Experimental Program

The experimental program for the characterization of the in-plane behavior of traditional brick masonry infill walls typical of south European countries was based on static cyclic in-plane tests. For this, three brick masonry infilled rc frames were considered. Additionally, two additional rc frames with strengthened masonry infills were tested by using the same experimental setup and protocol. The strengthening of the masonry infilled frames was carried out by adding textile meshes embedded in rendering mortar (textile reinforced mortar – TRM) to the brick masonry infilled frames. Taking into account the limited facilities at the laboratory of Civil Engineering at University of Minho and to avoid difficulties in handling full scale specimens, it was decided to design reduced scale specimens to represent the full scale rc frame with infill wall Characterization of Prototype and designing reduced scale specimens.

An overview of the scaled reinforcement scheme of the rc frame and of the cross sections of columns and beams are shown in Figure 1 and Figure 2

In total, five specimens were considered in the experimental campaign (Table 1), namely one bare frame (specimen BF-I), one unstrengthened infilled frames and two strengthened specimens with TRM technique. It is stressed that the unstrengthened specimen was tested until in-plane drift of 1%. In the strengthened specimens two different types of reinforcing meshes were used, namely a commercial mesh (specimen SIF(CTRM)-I-B) and the textile mesh developed at University of Minho (specimen SIF(DTRM)-I-B), see Figure 3. It should be mentioned that the workmanship used in the construction of the unstrengthened specimen loaded until collapse was different from the workmanship used in the construction of the remaining specimens. For the specimen loaded until collapse, the workmanship is considered as type "A" and for the other specimens the workmanship is denoted as type "B". The steel used for the construction of rc frame was of class A400NR, with a yielding tensile strength of 400MPa and for the concrete, a C20/35 class was adopted.

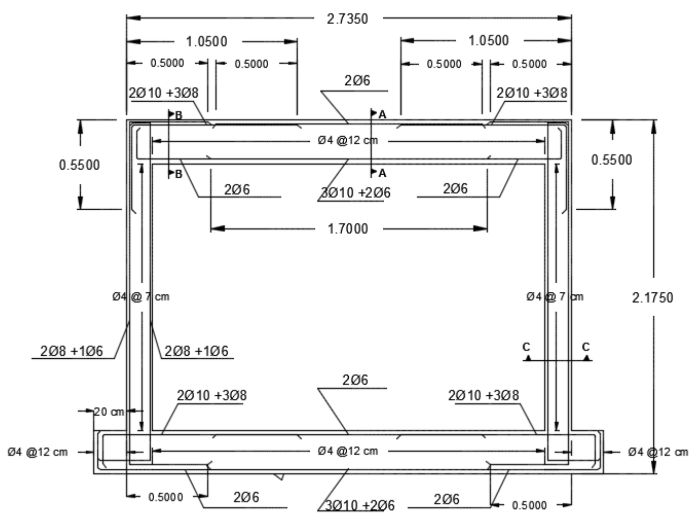


Figure 1 Geometry and reinforcement scheme of the reduced scale rc frame

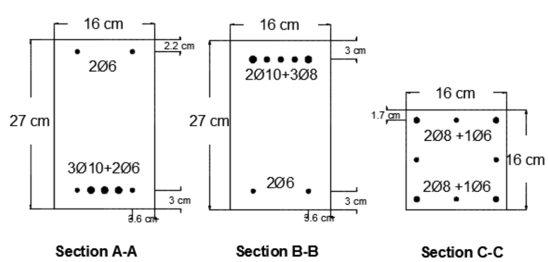
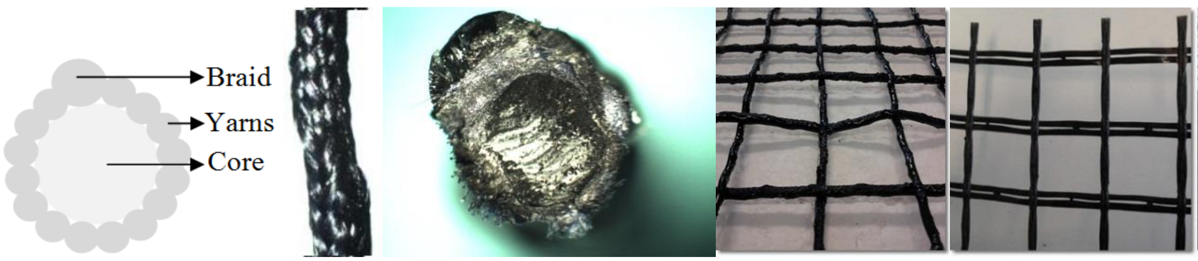


Figure 2 Cross-sections of columns and beams in reduced scale rc frames

Table 1 Designation of the specimens for in-plane static cyclic loading

Name	**Type of specimen**	**Type of loading**	**Number of leaves during**	**Group of Mason**

			construction	
BF-I	Bare frame	In-plane	-	
SIF-I-A	Solid infilled frame	In-plane	Double leaf	A
SIF-I(1%)-B	Solid infilled frame	Prior In-plane drift of 1%	Double leaf	B
SIF(DTRM)-I-B	Solid infilled frame strengthened with TRM-designed mesh	In-Plane	Double leaf	B
SIF(CTRM)-I-B	Solid infilled frame strengthened with TRM-commercial mesh	In-Plane	Double leaf	B

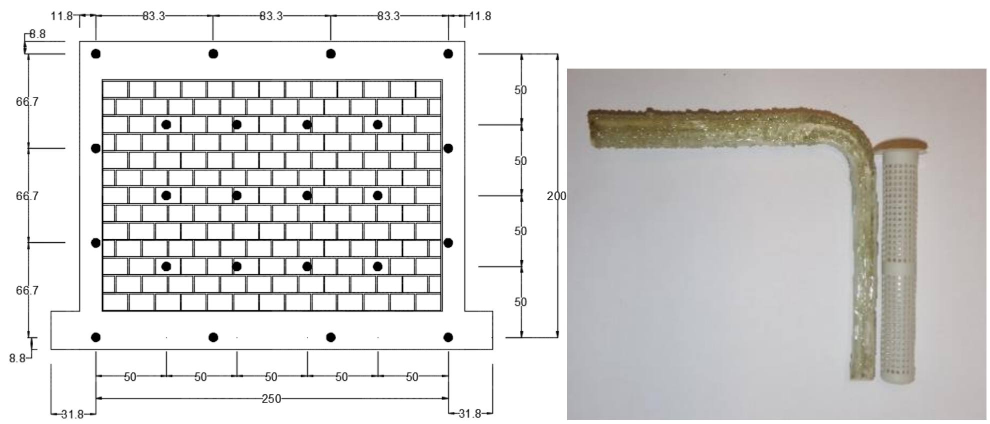


(a) (b) (c)

Figure 3 Details of braided rods and meshes; (a) cross section of a braided mesh [20]; (b) designed mesh; (c) commercial mesh

2.1 Construction and strengthening of the specimens

The rendering mortar used in the strengthened specimens was a pre-mixed commercial mortar indicated to be applied with the selected commercial textile mesh and was applied in both external surfaces of internal and external leaves. A multipurpose latex 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 detachment of the rendering mortar (Figure 4a). The application of reinforced rendering to the masonry infills was carried out in the following steps: (1) definition of the pattern for pilot holes (Figure 4a) to place the connectors aiming at improving the adherence of the rendering mortar to the masonry infill; (2) drilling and cleaning the holes and insertion of plastic row plugs shown in Figure 4b in the holes (Figure 5a); (3) application of the first thin layer of about 5mm of mortar (Figure 5b); (4) injection of a chemical anchor into the holes and inserting the L-shaped glass fiber connectors; (5) positioning of the textile mesh on the first layer of mortar; (6) application of the second layer of mortar and rectifying the rendered surface, see (Figure 5c,d). The total thickness of the rendering was measured as approximately 20mm in all the specimens. The application of the rendering in two successive layers enables the involvement of the textile mesh by the mortar and also adequate development of the adherence between them.



(a) (b)

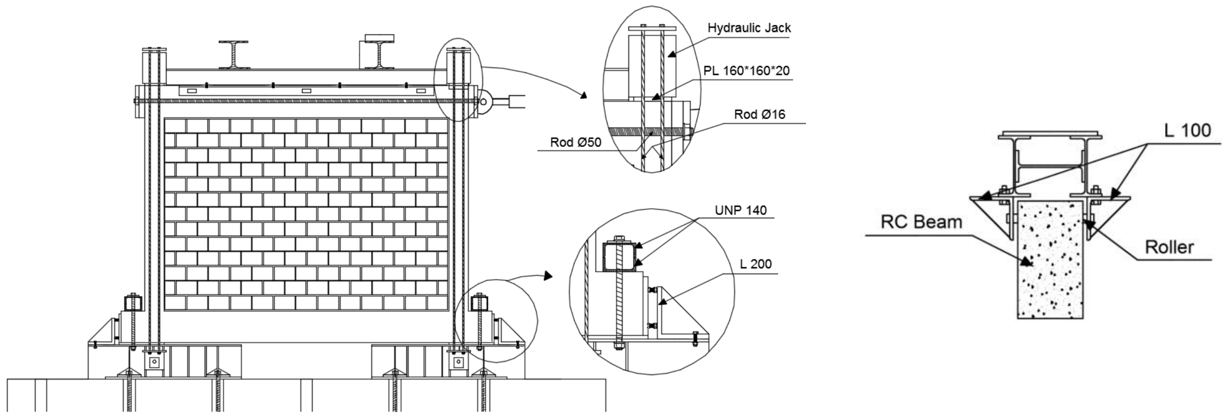
Figure 4 Details of the mesh connectors; (a) pattern of the connectors (b) plastic row plug and glass fiber connector

(a) (b) (c) (d)

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

2.2 Experimental setup and instrumentation

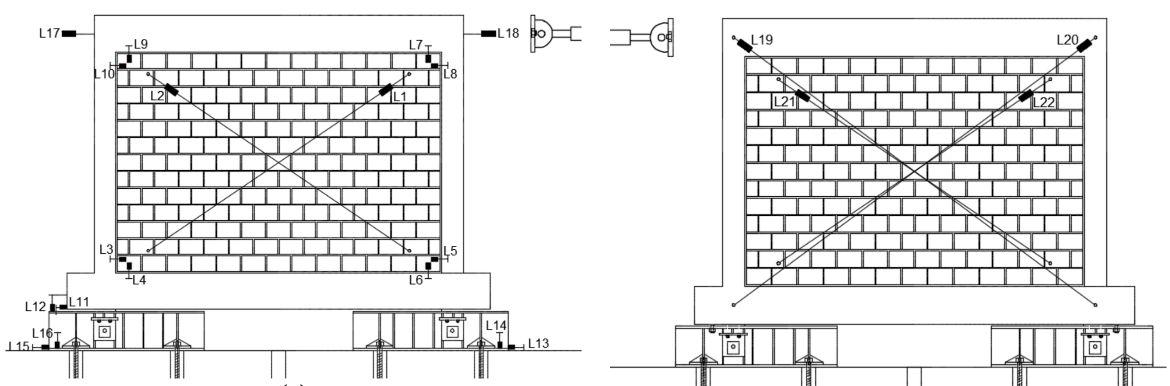
The test setup designed for the static cyclic in-plane testing of the rc frames with masonry infills is shown in Figure 6. Two vertical jacks were placed on the top of the columns to apply the vertical load of 160 kN, corresponding to 40% of the column's axial force capacity.



(a) (b)

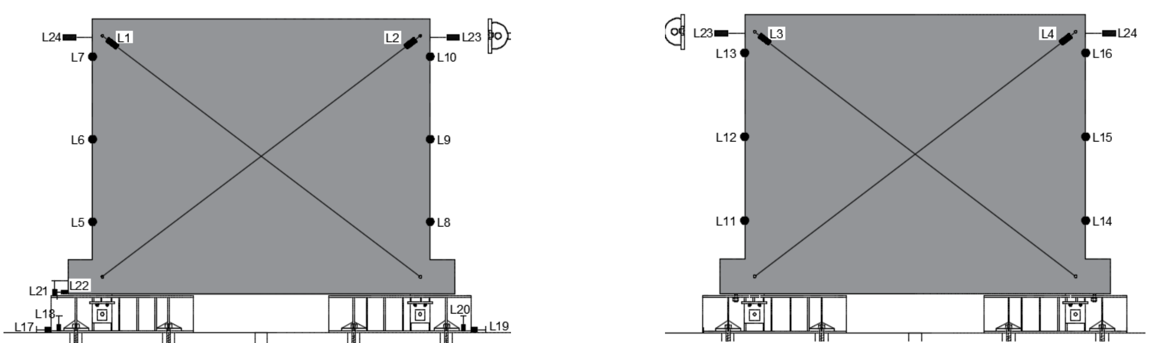
Figure 6 a) Test setup for in-plane cyclic loading b) out-of-plane support of the upper beam in the in-plane testing

The instrumentation adopted for the measurement of the most relevant displacements during the static cyclic in-plane testing is shown in Figure 7 and the instrumentation of the strengthened specimens was defined to have the response of both leaves recorded, see Figure 8.



(a) (b)

Figure 7 Instrumentation for in-plane loading; (a) external leaf (b) internal leaf



(a) (b)

Figure 8 Instrumentation of the specimen for in-plane loading; (a) external leaf (b) internal leaf

2.3 Loading Protocol

The in-plane static cyclic tests were performed in displacement control by imposing increasing pre-defined levels of displacements through an LVDT connected to the horizontal hydraulic actuator. The loading protocol adopted for in-plane static cyclic testing, which is in accordance with the guidelines provided by FEMA 461[1], is shown in Figure 9. The loading protocol includes sixteen different sinusoidal steps, starting from a displacement of 0.5mm, representing 0.03% drift, calculated as the ratio between the top lateral displacement and the height at which the horizontal load is applied from the base of the frame.

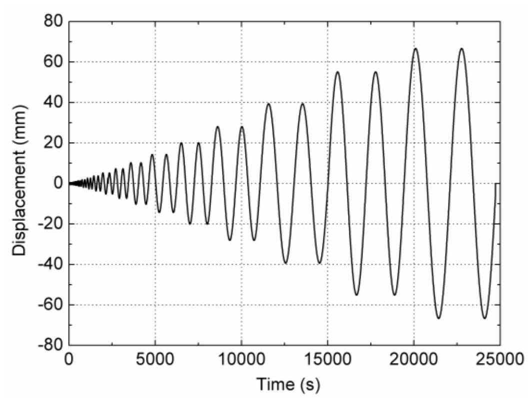


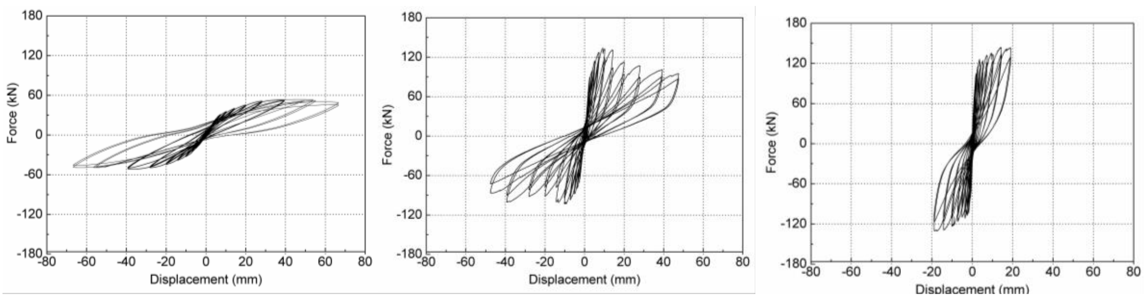
Figure 9 Displacement protocol for in-plane testing

3 Experimental results and discussion

3.1 Force-displacement diagrams

The lateral force-displacement diagrams obtained for the different unstrengthened specimens tested under cyclic in-plane loading are shown in Figure 10 . The positive direction is considered to be the direction in which the hydraulic actuator pushes the specimen whereas the negative direction is the direction in which the actuator pulls the specimen through two plates that were connected with two thick steel rods.

It is important to note that both lateral strength and initial stiffness of the rc frame with masonry infill are significantly higher than the values found for the bare frame, which confirms the role of the masonry infill in the lateral strength of the rc frames. The lateral displacement at which the lateral resistance is attained is much lower in case of the rc fame with masonry infill, which is related to the higher stiffness of the infilled frame. The force-displacement diagrams are characterized by an initial linear behavior corresponding to the elastic behavior of the structure. After the onset of cracking, the nonlinear behavior is visible both through the nonlinearity of the force-displacement envelop and through the higher hysteresis corresponding to the development of damage and dissipation of energy. Given the shape of the hysteretic force-displacement diagram, it is expected that the energy dissipation is higher in the rc frame with masonry infill, being associated to the cracking development in the masonry wall. The strength degradation in the second cycle starts after cracking and increases as the damage accumulation increases. This is particularly evident in the complete force-displacement diagram of rc frame with masonry infill built with mason A tested until failure.

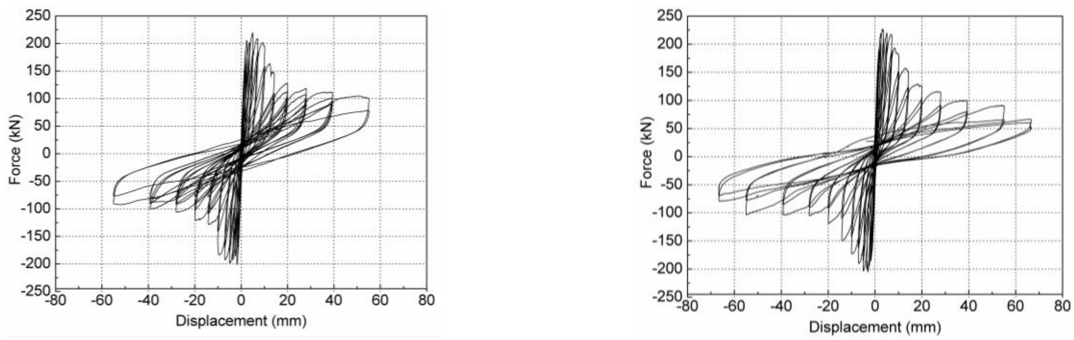


(a) (b) (c)

Figure 10 Force-displacement diagram; (a) bare frame; (b) specimen SIF-I-A;e) specimen SIF-I(1%)-B

It is noteworthy to mention that the specimen SIF-I(1%)-B was tested until lateral drift of 1% to investigate the effect of prior in-plane damage on the out-of-plane loading. After finishing the in-plane loading, it was subjected to the out-of-plane loading.

The cyclic force-displacement diagrams obtained for the masonry infilled frames strengthened with textile reinforced mortar are shown in Figure 11. The most relevant difference with respect to the complete response of the rc frame with masonry infill built with mason A is the increase of the stiffness and lateral strength. The nonlinear behavior before the peak is more limited in the strengthened masonry specimens, when compared with the rc frames with masonry infill. The deformation capacity of these specimens is higher than the deformation attained in the unstrengthened specimens but the plastic deformation is higher, which should be associated to more permanent damage. The post-peak behavior is very controlled, meaning that very progressive and smooth reduction of the lateral loadbearing capacity of the composite structure is observed. The ultimate lateral drift is slightly higher in case of the specimen strengthened with the designed textile mesh (SIF(DTRM)-I-B) when compared to the specimen strengthened with the commercial mesh (SIF(CTRM)-I-B), but it should be stressed that there are no significant differences between both strengthened specimens. This appears to indicate that the role of the textile meshes is very close.

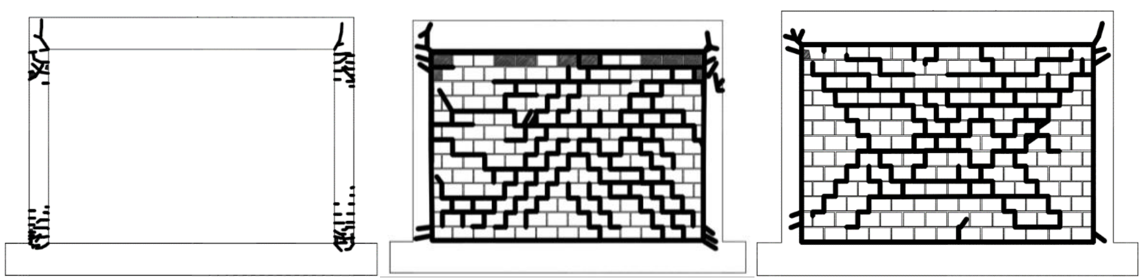


(a) (b)

Figure 11 Force-displacement diagram (a) specimen SIF(CTRM)-I-B; (b) specimen SIF(DTRM)-I-B

3.2 Crack patterns

The final cracking pattern developed in the cavity walls during the cyclic in-plane tests are shown in Figure 12.



(a) (b) (c)

Figure 12 Final cracking pattern of the bare frame; (b) specimen SIF-I-A at end of the test; (c) specimen at lateral drift of 1%;

It is clear that the final cracking patterns of the bare frame show that all the cracks are mostly concentrated in the columns, indicating the development of plastic hinges at the top and bottom part of the columns.

The final cracking patterns observed in the specimens strengthened with textile reinforced mortar are presented in Figure 13. It is noticed that smeared cracking pattern is observed in the mortar layers of the specimen strengthened with the commercial glass fiber mesh. The cracks developed mostly along the diagonals and some horizontal cracks at the level of the upper and bottom interfaces between the masonry infill and rc frame were also observed. These horizontal cracks should indicate the trend of separation of the masonry infill from the rc frame. In case of the specimens strengthened with bi-directional mesh composed of braided composite rods, only few cracks were developed in the reinforced mortar layer. Horizontal cracking was visible along the infill-rc frame interfaces. Some small cracks were also observed in the areas where the shear connectors were totally failed. The strengthening mortar layers started to detach from the rc frame at early stages of loading (lateral drift of 0.07% in both directions) as observed from the evolution of the displacement measured at the LVDTs placed to measure eventual debonding of the mortar layer, see Figure 14. From the results obtained, it seems that other type of connectors should be used in the rc fame. Besides, it should be mentioned that the failure of the connectors of the rc frames is brittle and, thus, more ductile material should be selected. On the other hand, it is mentioned that the connectors behaved in appropriate way in case of brick infill, as no detachment of the reinforced mortar layer from the masonry infill was detected. It is observed that the displacements measured by different LVDTS are very similar, which indicates that the separation of the mortar layer from the rc frame was practically uniform along the height of the specimen.

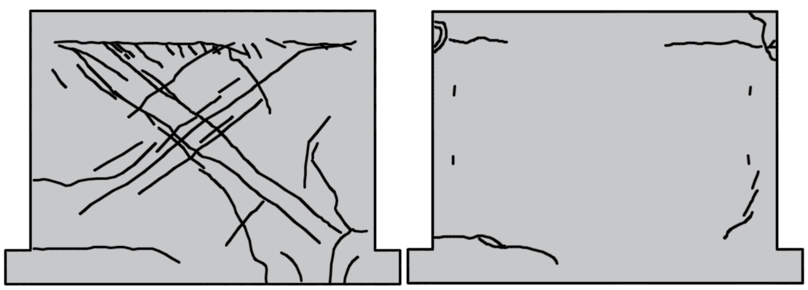
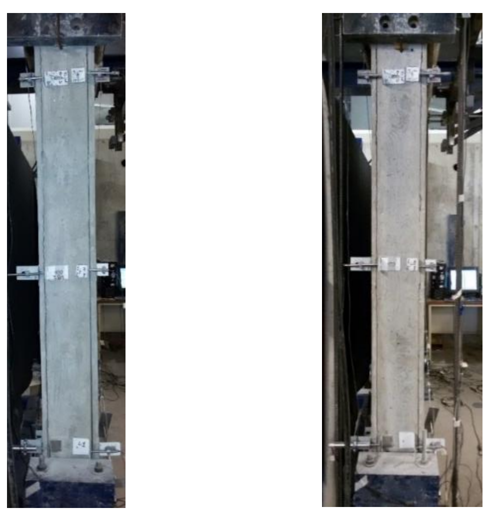


Figure 13 Cracking pattern in the rendering mortar at the end of the test; (a) specimen SIF(CTRM)-I-B; (b) specimen SIF(DTRM)-I-B



(a) (b)

Figure 14 Detachment of the reinforced mortar layer from the rc frame (a) specimen strengthened with commercial mesh at lateral drift of 0.27% b) (a) specimen strengthened with developed mesh at lateral drift of 0.20%

3.3 Evaluation of in-plane performance

Based on the force-displacement diagrams of the specimens, the key parameters were derived and shown in Table 2. The comparative analysis among the curves enables to identify clearly the differences among the distinct specimens. These envelops are used to define the key parameters for systematic comparison of the in-plane response of the rc frames with masonry infills, namely: (1) the lateral force corresponding to the crack initiation, H_{cr}, and the corresponding lateral displacement, d_{cr},; (2) the secant stiffness at the first cracking point, calculated as the ratio between the crack initiation force and crack initiation displacement; (3) the maximum lateral force, H_{max}, and the corresponding lateral displacement, d_{Hmax}. It is clear that the presence of infill significantly increases the initial stiffness and lateral strength of the rc bare frame. This increase in the initial stiffness and lateral strength is about 5.2 and 1.25 times in case of brick infill built with mason A. In case of brick infill built with mason B, the improvement on the initial stiffness and lateral strength is even higher, being approximately 14.9 and 1.9 times respectively. Additionally, it is observed that the initial stiffness of specimens built with masonry B is more than the double of the initial stiffness recorded for the specimen built by the first mason (mason A). The lateral strength obtained in the specimens built with mason B is around 30% higher than the lateral strength obtained in the specimen built with mason A. This result highlights again the importance of the workmanship used in the construction of brick infills in the in-plane behavior.

Table 2 Key parameters characterizing the in-plane behavior of tested specimens

	Positive direction					Negative direction				
	H_{cr} (kN)	d_{cr} (mm)	K_e (kN/mm)	H_{max} (kN)	d_{Hmax} (mm)	H_{cr} (kN)	d_{cr} (mm)	K_e (kN/mm)	H_{max} (kN)	d_{Hmax} (mm)
Bare Frame	19.2	3.7	5.1	53.9	53.8	-12.2	-2.7	4.6	-51.4	-39.3
SIF-I-2L(NC)-A	89.0	2.7	33.4	133.9	10.3	-52.3	-1.9	27.4	-103.6	-10.3
SIF – I(1.0%)-B	72.5	0.98	74.0	143.9	14.35	-80.2	-0.95	84.4	-130.6	-19.05
SIF(CTRM)-I-B	185.0	1.84	100.8	219.2	5.15	-201.1	-1.82	110.5	-201.1	-1.82
SIF(DTRM)-I-B	195.9	1.85	106.1	227.1	3.60	-185.1	-1.79	103.5	-205.3	-3.62

The role of the textile reinforced mortar on the in-plane behavior is reflected very clearly in the load corresponding to the initiation of cracking, which is considerably higher than the one obtained in the specimens without reinforcement. The addition of the reinforced mortar layer by using different textile meshes resulted in very close lateral performance, increasing the in-plane lateral stiffness and resistance of unstrengthened specimens of about 40%. The limited amount of increase, can be related to the detachment of the TRM layer from the masonry.

4 Conclusions

Based on the test results of the experimental program, the following conclusions can be drawn for the in-plane behavior of infilled frames:

1) The presence of low strength cavity brick walls within the bare frame increases the initial stiffness and lateral strength of the bare frame significantly. The increase in the initial stiffness ranges from 5.2 to 14 times and in the lateral strength ranges from 1.3 to 1.9 times, depending on the quality of workmanship. This also indicates that the specimens constructed by experienced mason demonstrated higher initial stiffness and lateral strength. It is revealed that, both leaves of the cavity walls behave in a similar way, demonstrating that both leaves are contributing to the lateral strength and stiffness of the composite structure.

2) It is also concluded that presence of infill within the bare frame limits the amount of damage in the bare frame considerably due to in-plane loading.

3) The textile reinforced mortar (TRM) technique enhances the in-plane behavior of infilled frame, namely the initial stiffness and lateral strength.

4) The textile meshes are also important to control the damage in the masonry infills. It is observed that much lower cracking was developed in the brick masonry infills strengthened with textile reinforced mortar.

5) It is clear that the effectiveness of the retrofitting technique in the in-plane direction by using developed textile meshes is similar to the commercial meshes which validates the use of textile mesh based on the composite braided rods.

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