PERFORMANCE OF TEXTILE REINFORCED MORTAR AS STRENGTHENING SOLUTION OF MASONRY INFILL WALLS TO...

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PERFORMANCE OF TEXTILE REINFORCED MORTAR AS STRENGTHENING SOLUTION OF MASONRY INFILL WALLS TO SEISMIC ACTION

F. AKHOUNDI
Investigador
ISISE
Portugal

G. VASCONCELOS
Prof. Auxiliar
ISISE
Portugal

L. SILVA
Investigador
ISISE
Portugal

P. LOURENÇO
Prof. Catedrático
ISISE
Portugal

R. FANGUEIRO
Prof. Auxiliar
2C2T
Portugal

F. CUNHA
Investigador
2C2T
Portugal

SUMÁRIO

A elevada vulnerabilidade sísmica das paredes de enchimento em alvenaria tem conduzido à necessidade de reforço deste tipo de paredes, utilizando técnicas convencionais ou usando materiais inovadores. Os Fiber reinforced polymers (FRP's) são utilizados principalmente como materiais inovadores para o reforço de estruturas. Apesar das vantagens associadas ao uso deste tipo de materiais, esta técnica de reforço apresenta algumas desvantagens, como problemas de aderência, mau comportamento à humidade e ao fogo.
Uma solução possível para os problemas associados a estes materiais, pode passar pela substituição de agentes ligantes orgânicos para os inorgânicos, tais com argamassas à base de cimento. As interações entre as fibras e a matriz e também as condições de aderência em compósitos cimentícios pode ser melhorado através da utilização de malhas de reforço embebidas na argamassa de reboco, técnica habitualmente designada em língua inglesa por textile reinforced mortar (TRM). Esta técnica é relativamente nova (utilizada desde dos anos 80), tendo sido estudada por vários investigadores em diferentes aplicações.
Neste artigo, investiga-se a utilização desta técnica no reforço de paredes de enchimento de alvenaria para ações no plano que simulam a ação sísmica. Foram ensaiados no plano, três provetes à escala reduzida, representativos da construção dos anos 70 em Portugal, um provete de referência, um provete reforçado com uma malha comercial e um provete reforçado com uma malha de reforço desenvolvida para o efeito. Neste caso as malhas de reforço foram desenvolvidas na Universidade do Minho no departamento de engenharia têxtil. A eficácia da técnica desenvolvida foi comparada com soluções comerciais.

ABSTRACT

The high seismic vulnerability of masonry infilled frames have lead to their in-plane and out-of-plane strengthening by means of conventional techniques or by using innovative materials. Fiber reinforced polymers (FRP's) are mostly used as innovative materials for retrofitting of structures. In spite of many advantages associated with use of FRPs, this retrofitting technique is not problem-free

One possible solution to the problems of FRPs could be the replacement of organic binders with inorganic ones such as cement based mortars. Fiber-matrix interactions and also the bond conditions in cementitious composites could be improved if the fibers replaced with textile sheets. This lead to the formation of textile reinforced mortar (TRM) technique. This technique is relatively a new technique (it was started to use in early 1980s) and was studied by few researchers.

In this paper, in-plane retrofitting of the infilled frames was investigated by using textile reinforced mortar (TRM) technique. Three half scale specimens which are representative of construction of 1970s in South European countries, were tested in the in-plane direction, a reference specimen, specimen retrofitted by commercial TRM technique and specimen retrofitted with developed TRM technique. In the developed TRM technique the textile meshes were developed and produced in the Textile Department. The effectiveness of the developed technique was compared with commercial solutions.

KEYWORDS: Masonry Infilled Frames, In-plane, Airbag, Retrofitting, Textile Reinforced Mortar (TRM)

1. INTRODUCTION

Past earthquakes such as Mexico City earthquake in 1985 [1], Kocaeli (Turkey) earthquake in 1999 [2] Bhuj earthquake in 2001 [3], L'Aquila earthquake in 2009 [4] have confirmed that masonry infills can affect the behaviour of the reinforced concrete (RC) or steel frames. Presence of infills can have negative effects on the local or global behaviour of the buildings. As it is shown in Figure 1, the formation of the short column phenomenon happens when masonry infills leave a short portion of the column clear, leading to the shear collapse of the columns. The soft story phenomenon can be observed when the distribution of the infill walls along the height of the structure is irregular.

(a) (b)

Figure 1: Negative effects of infill panel in structure; (a) soft story mechanism [5], (b) short column mechanism [6].

The high seismic vulnerability of these kind of structures observed during last decades has promoted the researchers to develop relevant techniques for their retrofitting. With this respect, conventional techniques or innovative materials for in-plane and out-of-plane strengthening has been presented. The advantages and disadvantages of the conventional technique is deeply discussed in [7, 8]. For instance, using jacketing technique needs evacuation of the buildings and also adds heavy mass to the building which totally changes the dynamic behaviour of the structure. In terms of advanced strengthening techniques, composite materials have been received large attention from the research community and they have been already applied in real context. The fiber reinforced polymers (FRP's) are a class of advanced composite polymers that have been widely used in space industries and due to its exclusive characteristics like lightweight, corrosion resistance, good mechanical properties and easiness of installation is one of the most common materials in the field of civil engineering [9]. With this regard, different researchers investigated the effect of using FRPs on the in-plane [10-14] and out-of-plane [15, 16] behaviour of masonry infilled frames.

The effect of different FRP configuration on the in-plane behaviour of infilled frames were investigated by Yuksel et al (2010) and Ozkaynak et al (2011) [13, 17]. It is observed that all the FRP retrofitting configurations increase the strength of the system by a factor of 14-69%, stiffness by a factor of 2.86-4.03 times and energy dissipation capacity by a factor of 0.5 to 1.5 times when compared with un-retrofitted system.

In the study carried out by Altin et al [10], ten specimens of masonry infilled non-ductile RC frames retrofitted by CFRP laminates in diagonal configuration were tested under in-plane cyclic loading. It was observed that the specimens receiving CFRP strips in diagonal configuration showed higher lateral strength and stiffness. It was also found that the lateral strengths of specimens with CFRP strips on both sides of the infill wall increased by 2.18 and 2.61 times when compared to the values obtained in specimens with CFRP strips on one side only. The increase in lateral stiffness for the same specimens was 4 and 6 times in relation to the reference specimen. The specimens with CFRP strips installed on the interior side have the same strength and stiffness as the specimens with CFRP on exterior side. Therefore, if it is desired to use FRP sheets in only one side, there is no difference to install the FRP sheet on interior or exterior side. Another contribution of this study is that when the width of the CFRP increases, the increase in strength and stiffness can be limited.

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 behaviour 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 behaviour could inhibit the use of FRP [18]. 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 use in early 1980s) and has been studied by few researchers [18-21].

The experimental work carried out by Papanicolaou et al [21] on different masonry wallets subjected to in-plane and out-of-plane cyclic loading also revealed that TRM enhances the in-plane and out-of-plane behaviour of masonry. For out-of-plane loading, the TRM is more effective than FRP in terms of lateral strength and displacement at failure. For the case of in-plane loading, TRM (compared with FRP) result in reduced effectiveness for strength (but not more than 30%). Nevertheless, in terms of deformation capacity (being of crucial importance in seismic retrofitting of unreinforced masonry walls) TRM is more effective than FRP.

In a recent study carried out by Da Porto et al [22] 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. In this context the solutions were considered as; 1) special lime-based plaster with geo-polymer binder 2) bidirectional composite meshes applied with inorganic materials (TRM) 3) TRM improved by anchorage of the mesh to the 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 application of special plasters or TRM strengthening systems does not significantly change the initial stiffness or maximum in-plane resistance of the reference frame. The main contribution could be related to reducing the damage in the infill.

2. EXPERIMENTAL PROGRAM

Geometry and reinforcement scheme of the reduced scale specimens which are the representative of the construction types of 1970s in the Southern European Countries are shown in Figure 2 and Figure 3. Cauchy's similitude law was applied to design the half-scale specimens based on the geometry of the prototype.

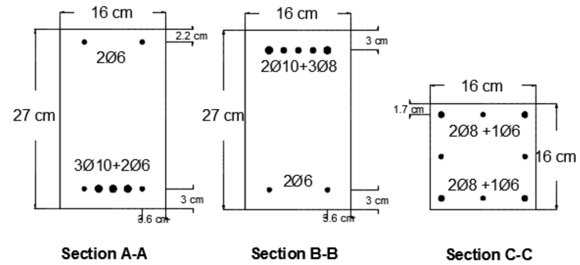


Figure 2: Cross-sections of columns and beams in reduced scale specimens.

Three full infilled specimens were constructed for testing, with two leafs one of 60mm (internal leaf) and other of 80mm (external leaf).

Two of the specimens were retrofitted by TRM technique; one with the meshes that were developed in the textile department of the University of Minho and another with the commercial textile meshes. In the first step of applying TRM technique on the specimens, number of twenty four holes based on the configuration of Figure 4 were drilled in the infill and bounding frame for installing the connectors to totally fix the applied TRM technique on the unreinforced specimen. The holes were cleaned with air to remove all the dust inside them; see Figure 5 (a) and (b). In the second step, one thin layer of rendering was applied on the specimen and the textile meshes were installed by fixing the connectors in the drilled holes; see Figure 5 (c) and (d). Finally, in the third step the final rendering was applied on the surface of the specimen and rectified; see Figure 5 (e). Final thickness of the rendering in all specimens was measured as 20mm.

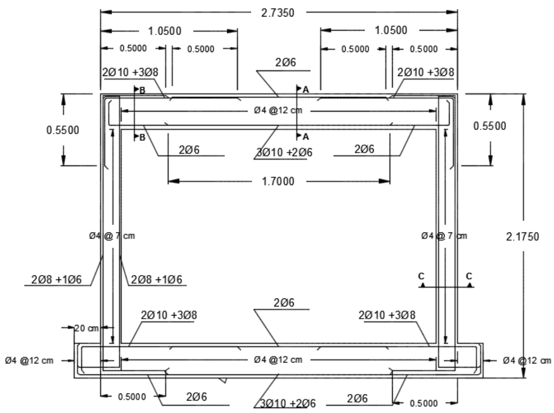


Figure 3: Geometry and reinforcement scheme of the reduced scale specimens.

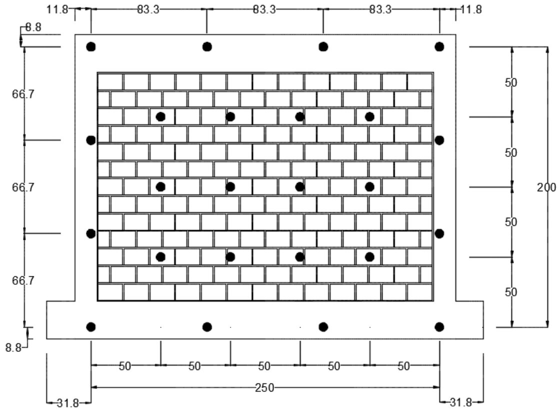
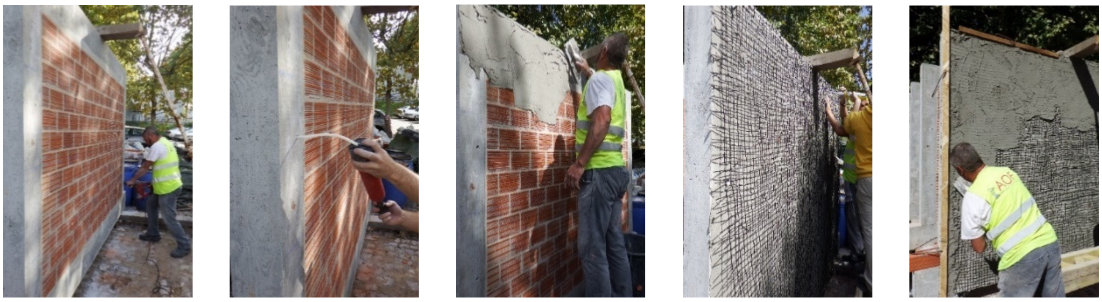


Figure 4: Location and number of the connectors to be fixed in the specimens.

Retrofitting of the specimens were applied for external surface of each leaf of the infill inside reinforced concrete frame. In the specimens for in-plane testing the infill contains two separate leaves in which their external surfaces were retrofitted. The rendering mortar used for retrofitting technique was mixed in a constant manner for all the walls to have the similar mechanical behaviour among them. One bag of cement called "Nivoplan" was mixed with 4 litres of water and 1 litre of planicrete that improves the plasticity of the mortar. Planicrete is used to improve the mechanical and adhesive characteristics of cement-based renders.



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

Figure 5: TRM retrofitting technique; (a) drilling the holes (b) cleaning the holes (c) casting thin-layer rendering (d) installing meshes on rendered surface by using shear connectors (e) final rendering and rectifying the rendered surface.

The test setup for the in-plane loading of the infilled frames is shown in Figure 6. The infilled frame was placed on two separated steel beams of HEA300 that were firmly attached to the strong floor to avoid their sliding on the floor. Also sliding of the infilled frame was prevented by bolting an L-shape steel profile of L200 to each side of the steel beam and its uplifting was also prevented by bolting two rectangular-shape steel profiles with M20 to the steel beams. The rectangular-shape steel profile was made by welding two UNP140 together. The out-of-plane movement of the enclosure frame was restrained by putting L-shaped steel frame of L100 on each side of the upper beam. Those profiles were bolted to the upper steel beams. Three rollers were placed on upper L-shaped profiles to completely minimize or even eliminate the friction between them and the upper reinforced concrete beam during in-plane loading.

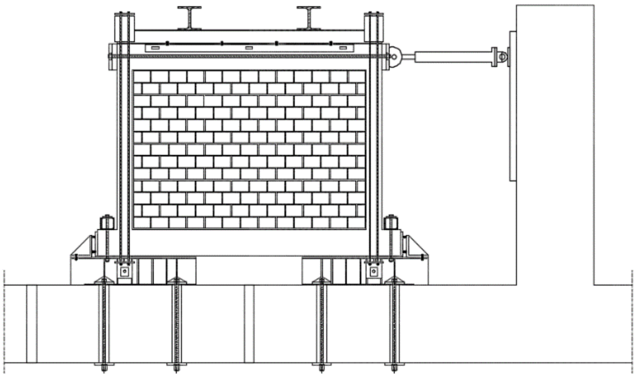
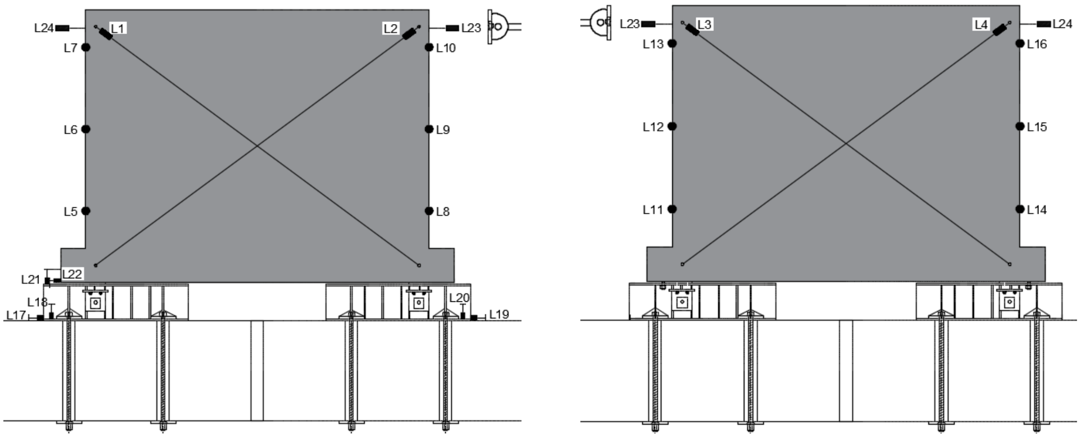


Figure 6: Test setup for in-plane cyclic loading.

Two vertical jacks were mounted on the top of the columns to apply the vertical load of 80 KN, corresponding to 20% of the column's axial force capacity. Those jacks are pinned to the lower steel beams by means of two vertical rods of φ16mm.
The instrumentation plan for the retrofitted specimens is shown in Figure 7. Four LVDTs (L1 to L4) were placed diagonally to monitor the diagonal deformation of the exterior and interior leaf. Twelve LVDTS (L5 to L16) were mounted on the retrofitted layer to capture the debounding of the added layer during in-plane loading. Six LVDTs of L17 to L22 were mounted to monitor the uplifting and sliding of the specimen towards ground and also steel profiles. Finally, two LVDTs of L23 and L24 were placed on the specimen to investigate the horizontal displacement of top RC beam in the direction of the applied load.



(a) (b)

Figure 7: Instrumentation of the specimen for (a) exterior leaf (b) interior leaf.

In-plane testing was performed under displacement control by imposing different pre-defined levels of displacement by hydraulic actuator. The loading protocol for in-plane quasi static cyclic testing which is in accordance with FEMA 461[23]. It is composed of sixteen different sinusoidal steps that starts from displacement of 0.5mm (0.03% drift) and ends in lateral displacement of 66.68mm (3.5% drift). Each step repeated two times except the first step that repeated six times. The amplitude a_{i+1} of step $i+1$ is 1.4 times of the amplitude a_i of step i as;

$$a_{i+1} = 1.4 a_i \quad (1)$$

Due to some limitation in the laboratory and hydraulic actuator the amplitude of the final step was selected as 1.2 times of the previous step.

3. EXPERIMENTAL RESULTS

3.1. Specimen retrofitted with commercial TRM

Force-displacement diagram of the specimen during in-plane loading is shown in Figure 8. It is clear that the specimen represents higher initial stiffness with respect to the unretrofitted specimens in the positive and negative directions. The first cracking of the specimen initiated at lateral drift of 0.1% corresponding to the lateral force of 201KN in the negative direction by formation of some horizontal cracks adjacent to the top interface between upper RC beam and infill. The maximum lateral force of the specimen in the negative direction was observed at this lateral drift. At the same lateral drift of 0.1% in the positive direction corresponding to the lateral drift of 185KN, cracking of the specimen started by formation of diagonal cracks in the mid-part of the infill. After initiation of the cracking in the specimen, applying further displacements in the positive direction leads to increase of the lateral force until it reaches the maximum lateral force of 219KN at lateral drift of 0.27% while in the negative direction, it causes decrease of the lateral force. Sudden drop in the lateral force of the specimen happens at lateral drift of 0.75% in the positive direction. This is calculated as 31% reduction in the lateral force of the specimen. It is related to the formation of more cracks in the specimen. In this lateral drift the specimen has lost its load bearing capacity due to high damages induced on it. Towards negative direction, sudden decrease of 30% in the lateral force is observed in the same lateral drift of 0.75%. In this direction it is also related to the high amount of damages induced in the specimen. After this point, applying further displacements in the positive and negative direction leads to gradual decrease of the lateral force as observed in Figure 8.

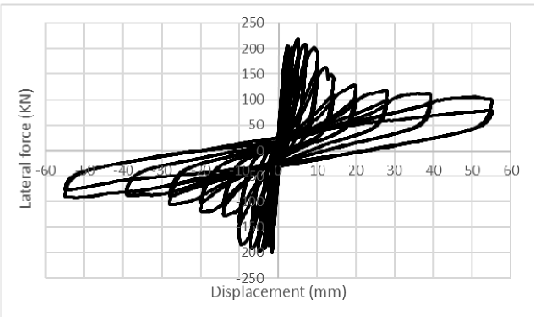


Figure 8: Force-displacement diagram of specimen retrofitted with commercial TRM.

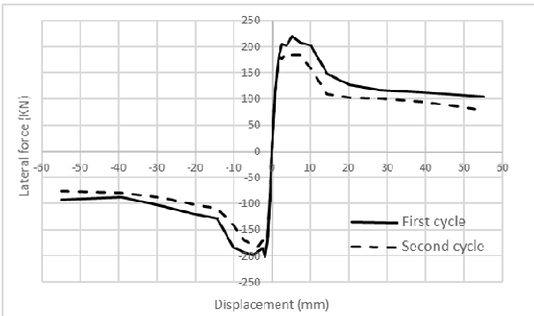


Figure 9: Monotonic force-displacement diagram of specimen retrofitted with commercial TRM at each successive cycles

Monotonic force-displacement diagram of the specimen at each cycle is shown in Figure 9. It is clear that there is no degradation in the lateral force until the initiation of cracks in the positive and negative directions. It is started at lateral drift of 0.1% where the cracking initiated in both directions.

Cracking pattern of the specimen is shown in Figure 10 and it is clear that it consists several diagonal cracks. During the in-plane loading it was observed that at the first levels of loading the retrofitting layer started to be detached from the RC frame. This was started locally at lateral drift of 0.07% from the upper left part of the infill at both interior and exterior leaves. The retrofitting layer of the exterior leaf was fully detached from the RC frame at lateral drift of 0.27% corresponding to the lateral force of 219KN

and of interior leaf was fully detached at lateral drift of 0.2% corresponding to the lateral force of 201KN.
The detachment of the retrofitting layer at the beginning and end of the test was shown in Figure 11. It is observed that the retrofitting layer was only detached from RC frame due to shear failure of the connectors that was placed in the RC frame. It was not detached from the infill at any point; see Figure 11 section "c". It seems that the shear connectors provided from the commercial company do not have enough shear capacity to resist the shear forces.

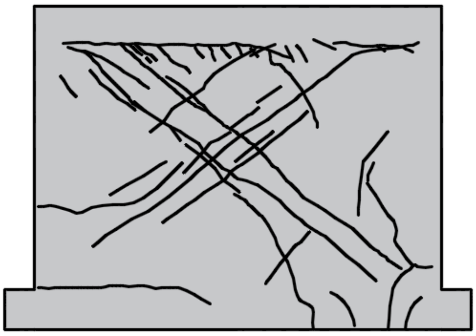


Figure 10: Final cracking pattern of the specimen retrofitted with commercial TRM.

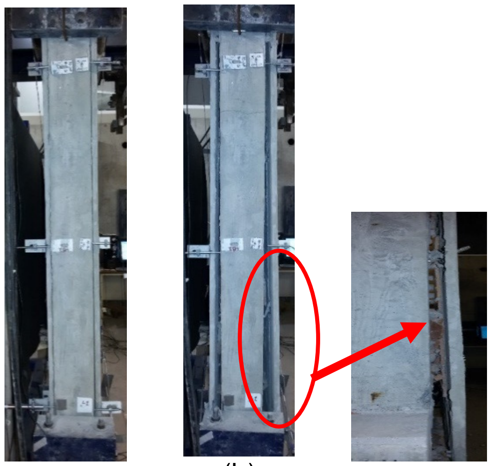


Figure 11: Detachment of the retrofitting layer at lateral drift of (a) 0.27% (b) 2.89% (c) Shear failure of the connectors between retrofitting layer and RC frame.

3.2. Specimen retrofitted with TRM technique by developed textile meshes

Force displacement response of the specimen due to the in-plane loading is shown in Figure 12. The specimen exhibits symmetric responses in the positive and negative directions. In the positive directions, the stiffness of the specimen starts to decrease by initiation of the cracks at lateral displacement of 1.85mm corresponding to lateral drift of 0.1% and lateral force of 195.9KN. The lateral force increases by applying further displacement in the positive direction until it reaches the maximum force of 227.1KN at lateral displacement of 3.6mm corresponding to the lateral drift of 0.2%. After this point, the stiffness of the specimen is reduced significantly and applying more displacements lead to reduction in the lateral force. The reduction in the lateral force is not obvious until lateral displacement of 7.2mm corresponding to the lateral drift of 0.38% while after this point increasing the lateral displacement leads to significant reduction in the lateral force. Towards the negative direction, the specimen shows linear response in terms of force-displacement diagram until initiation of the cracks at lateral displacement of 1.8mm corresponding to the lateral drift of 0.1% and lateral force of 185.1KN. Applying further displacements leads to gradual increase of the lateral force until it reaches the maximum force of 205.3KN at lateral drift of 0.2%. By applying further displacements, the lateral force remains unchanged until the lateral drift of 0.27% while after this point it leads to obvious reduction in the lateral force.
The monotonic force-displacement diagram of the specimen at each successive cycles is shown in Figure 13. It is obvious that there is no strength degradation in the specimen until lateral drift of 0.1% where the cracks initiates in the specimen. Degradation in the specimen starts after cracking of the specimen similar to what

observed in the previous specimens. More reduction in the lateral force of the specimen at the second cycle could be observed at higher lateral in-plane drifts where more cracks were formed in the specimen.

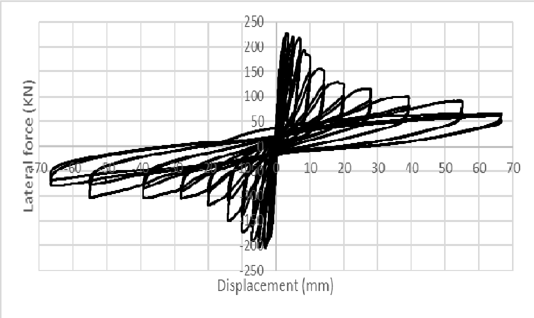


Figure 12: Force-displacement diagram of specimen retrofitted with TRM with developed textile meshes.

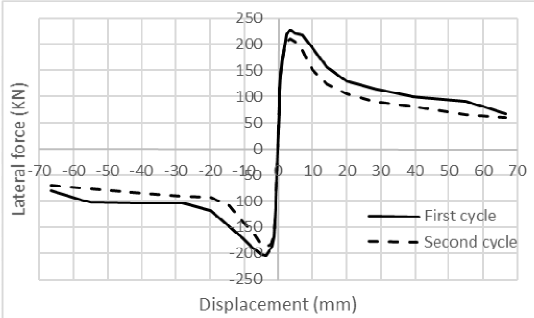


Figure 13: Monotonic force-displacement diagram of specimen retrofitted with developed TRM at each successive cycles.

Final cracking pattern of the specimen is shown in Figure 14.

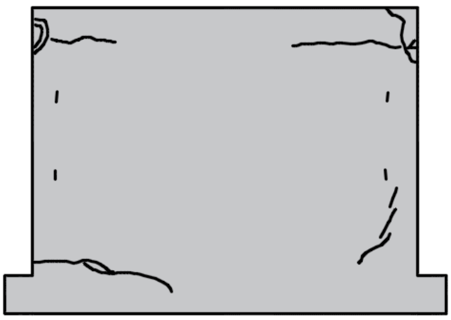
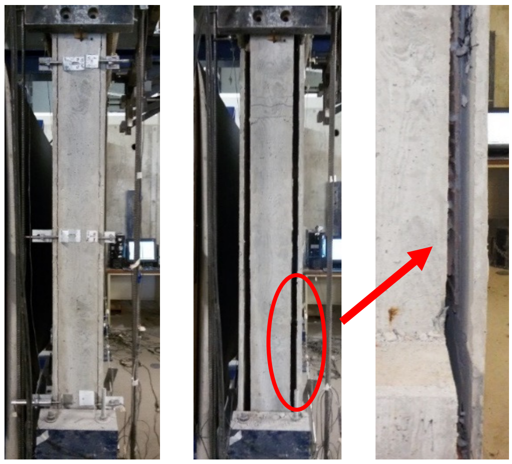


Figure 14: Final cracking pattern of the specimen retrofitted with developed TRM.



(a) (b) (c)

Figure 15: Detachment of the retrofitting layer at lateral drift of (a) 0.2% (b) 3.5% (c) Shear failure of the connectors between retrofitting layer and RC frame.

It is clear that there are few cracks in the retrofitting layer. This could be related to the delamination of the retrofitting layer from the RC frame at early stages of loading. The retrofitting layers started to be detached from the specimen at early stages of loading (lateral drift of 0.07% in both directions). At lateral drift of 0.2% corresponding to the lateral force of 227.1KN, the retrofitting layer was fully detached only from the RC frame at the side of exterior leaf. Due to this detachment the exterior leaf bulged at out-of-plane direction due to in-plane loading; see Figure 15. The same behaviour was also observed at interior side of the specimen. The retrofitting layer was fully detached from the RC frame at lateral drift of 0.2% and the interior leaf bulged at out-of-plane direction.

4. ANALYSIS OF THE RESULTS

Force-displacement diagram of the specimens are shown in Figure 16 and its parameters such as initial stiffness and lateral strength are represented in Table 1.

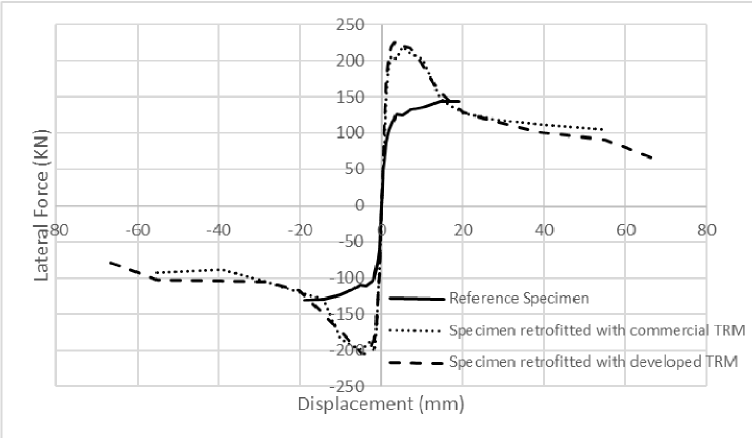


Figure 16: Force-displacement diagram of the specimens.

It is clear that retrofitting of the specimens with TRM technique increases the initial stiffness and lateral strength of the specimens. Initial stiffness of the specimens are calculated as the slope of the force-displacement diagram at 30% of the maximum force obtained for each specimen.

Table 1 - Initial stiffness and lateral strength of the specimens

Specimen		Reference	Commercial TRM	Developed TRM
Positive Direction	Stiffness (kN/mm)	65.1	100.8	106.1
	Strength (kN)	143.9	219.2	227.1
Negative Direction	Stiffness (kN/mm)	64.7	110.5	103.5
	Strength (kN)	130.6	201.1	205.3
Average	Stiffness (kN/mm)	64.9	105.7	104.8
	Strength (kN)	137.3	210.2	216.2
Percentage of Increase in	Stiffness (%)	-	63	62
	Strength (%)	-	53	58

It is also observed that the behaviour of both techniques; using commercial meshes and developed textile meshes are similar. For instance, it is concluded that using commercial meshes increased the initial stiffness and lateral strength of the specimen 63% and 53% respectively and using developed textile meshes increased them 62% and 58% respectively. This means that using textile meshes manufactured in the university could be economical as its results is similar to the commercial one. An important problem in the behaviour of the retrofitted specimens in which limits their effectiveness during earthquakes is delamination of the retrofitting layer from RC frame at early stages of loading. One solution to this problem could be replacement of the glass fiber shear connecters with steel shear connectors.

It is clear that during earthquakes, the infilled frames will behave in both in-plane and out-of-plane directions. When the connectors fail in the in-plane direction, they will lose their functionality to improve the out-of-plane behaviour of the specimen and also to protect their debris. It will be an important issue to use suitable connectors in the RC frame that have higher shear strength.

5. CONCLUSION

Based on the laboratory testing of the half-scale, one-bay one-storey masonry infilled frames the following conclusions could be made;

- Retrofitting of the masonry infilled frames with TRM technique could enhance their in-plane behavior by increasing their initial stiffness and lateral strength.
- The in-plane behavior of the retrofitted specimens; using commercial meshes and manufactured meshes is similar. This exhibits that the retrofitting of the specimens with textile meshes manufactured in the university could be assumed as cost-efficient technique.
- An important problem in the in-plane behavior of the retrofitted specimens is delamination of the retrofitting layer from RC frame by shear failure of the connectors provided in the RC frame. This will limit the effectiveness of this technique during earthquakes.
- It is recommended to replace the glass fiber shear connectors with steel connectors to enhance their effectiveness for shear loading.

6. ACKNOWLEDGEMENTS

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