Usage of ferrocement jacketing for strengthening of damaged unreinforced masonry (URM) walls

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ABSTRACT

In this paper, it is presented the usage of ferrocement jacketing technique as an effective method to improve structural performance of unreinforced masonry panels. Nine diagonal compression tests were conducted on plain, pre-cracked repaired and reinforced masonry panels on six specimen with nominal dimensions of 1.2 x 1.2 x 0.25 m, built and tested in laboratory. The results of the diagonal compression tests were compared in terms of increase in shear strength, drift and the mode of failure.

Additionally, finite element modelling using discrete micro-modelling and non-linear analyses were performed using midas FX+ for DIANA 9.6 commercial software to simulate the behavior of plain and reinforced panels.

As a result, it was observed that ferrocement jacketing made a considerable improvement in shear strength and deformation capacity for both, repaired and reinforced masonry panels.

Keywords: *ferrocement jacketing, URM, DIANA, diagonal compression test, repaired masonry, reinforced masonry*

INTRODUCTION

Unreinforced masonry (URM) buildings are one to the most used construction types in the world. Generally, these types of buildings have been designed (often not designed at all) to only resist gravitational loads and have been realized by rules of common practice. During their existence, many of those structures have suffered from the combined effects of inadequate construction techniques, seismic and wind loads, foundation settlements and deterioration of construction materials [1].

During an earthquake, the walls are subjected to a combination of lateral seismic forces, induced by the earthquake, that are in the form of out-of-plane or in-plane loading depending on the orientation of the building with respect to the earthquake epicenter. They manifest a brittle behavior and are very weak when subjected to such types of loads. The overall seismic performance of URM buildings depends on the capacity of in-plane walls to safely transfer the lateral loads to foundations. In this way, the masonry walls provide the post-earthquake stability necessary to avoid collapse of the entire structure [2].

As a result, it is the response of in-plane loaded wall that governs the global seismic performance of a URM building. In order to improve deficiencies related to poor structural performance of URM structures under seismic actions, various strengthening techniques have been developed and applied throughout history of construction. The main aim of the strengthening techniques is to increase low parameters of masonry such as tensile and shear strength as well as vulnerability against lateral loads. Traditional techniques such as: i) filling cracks and voids by grouting; ii) stitching of large cracks and weak areas with metallic or brick elements; iii) external or internal post-tensioning with steel ties; iv) shotcrete jacketing; v) ferrocement and vi) center core are available for retrofitting of existing masonry structures [3-4].

The main focus of this study is the ferrocement jacketing technique which is applied by embedding closely spaced meshes of fine rods with reinforcement ratio of 3-8% in high strength (15-30 MPa) cement-mortar layer of 10-50 mm thickness. The typical mortar mix consists of cement: sand ratios of 1: (1.5-3) with a w/c ratio of 0.4 [5]. It causes considerable increase in stiffness. Strengthening of pre-damaged URM walls can restore the original capacity and stiffness. Ferrocement can control crack formation as it has high flexural and shear strength.

It has been subject of many studies for both unreinforced masonry as well as concrete structures [6-9]. Kaushik et al.[10], observed that ferrocement provided an increase of strength and ductility for columns in both axial and eccentric loading conditions, improvement of cracking resistance [11], increased stiffness and ultimate load carrying capacity [12].

Some of the advantages of ferrocement such as considerably low price and ability to be completed with unskilled workers, make it an ideal solution for low cost housing.

It has been observed that the mesh helps to confine the masonry unit after cracking and it improves in-plane elastic deformation capacity. Abrams et al.[13], observed that the in-plane lateral resistance was increased 1.5 times during a static cyclic test. The out-of-plane behavior (arching action and out-of-plane stability) is improved too, as the ferrocement increases the wall height-to-thickness ratio [14-15].

In this paper, it is presented the usage of ferrocement jacketing technique as an effective method to improve structural performance of unreinforced masonry panels, its effectiveness in improving the structural performance of URM panels in diagonal compression testing following ASTM E 519-07 [16].

MATERIALS AND METHODS

The methodology followed in this study consists of destructive tests on masonry panels in order to determine the main mechanical properties of bricks, mortar and masonry assemblage. The testing procedures are the ones defined in American Society for Testing and Materials (ASTM) where are defined all the steps to be followed. These standards have been used by many researchers who have experimented with unreinforced clay brick masonry all over the world [1] [17-19].

Plain Panels

All the panels, were built using two leaf, English bond and new clay bricks with typical nominal dimensions of 243.4 mm x 118.9 mm x 56.8 mm with 15 mm thick mortar joints made of hydraulic cement mortar of type “N” with a volumetric mix ratio of cement: lime: sand, 1:1:6 (Figure 21). The specimen are part of a wider experimental campaign conducted by the authors for a research project at Epoka University.

Figure 21. Construction process of plain walls.

Ferrocement jacketing reinforced panels

W-10-FC, W-11-FC and W-12-FC panels were reinforced using ferrocement jacketing; attachment of a double-layered galvanized steel mesh on both sides of the plain wall (**Error! Reference source not found.**). The mesh is fixed to the wall by means of mechanical anchors and common mortar. The dimensions of the steel mesh are equal to the plain wall (1.2 m x 1.2 m). Allowance of 1.5-2 cm on each side shall be made in order to have a proper jacketing of the wall. The galvanized steel mesh is fixed using anchors (threaded bolts of diameter 8 mm and length 70 mm with washers, mounted on previously drilled holes, having 10-mm wall plugs on the bricks at a distance of 30 cm). The spacing of the connections was slightly changed depending on the brick arrangements, in order to make sure that the connection was done on the brick and not on the mortar joint. The process of mounting the steel mesh on the faces of the wall should be done carefully in order to lay the layers properly, as well as to provide a 5-10 mm allowance between mesh and the bricks for plaster mortar. The mortar mix is prepared using cement: sand 1:4, by volume and water/cement ratio of 0.4.

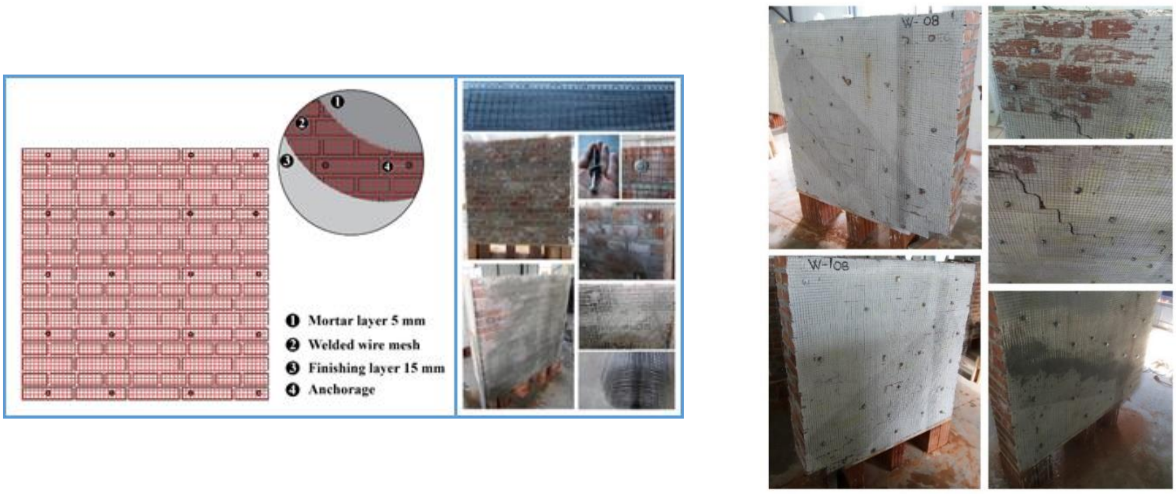

Figure 2. Plastering process with ferrocement jacketing (FC) (schematic view and application) (left) and repairing with ferrocement (right).

Ferrocement jacketing repaired panels

The procedure of repairing of the damaged walls with ferrocement is the same as strengthening of the plain walls.The only difference is application of an extra layer of galvanized steel mesh along the diagonal cracks of the damaged wall (Figure 2). This layer is fixed using extra anchors drilled every 30 cm along the diagonal.

Determination of Diagonal Tensile Strength

ASTM E 519-07 [16] is a test method used to determine the diagonal tensile or shear strength of 1.2 by 1.2 m masonry assemblages by loading them in compression along one diagonal, thus causing a diagonal tension failure with the specimen splitting apart parallel to the direction of load (Figure 3).

The movable test set-up consists of two loading shoes placed on two diagonally opposite corners of the panel connected by four high strength steel rods positioned along the compressed diagonal. The 50-tonne-capacity hydraulic jack was incorporated between the top loading shoe and a metallic plate connected to the steel rods, which when loaded, developed tension forces on the four steel rods connecting the loading shoes, compressing the wall diagonally, providing the desired failure mode; diagonal cracking and/or bed joint sliding failure.

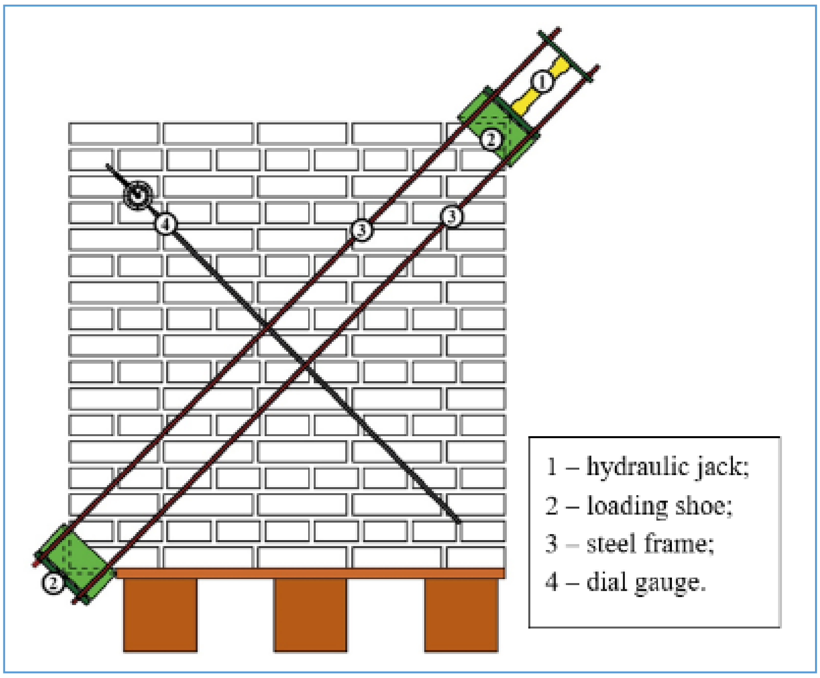

Figure 3. Diagonal compression test set-up.

Numerical modelling

The model was created in midas FX+ for DIANA 9.6. The mesh of the model was done following three main stages: firstly the half-brick was created with interface elements to represent the brick crack and the brick joint, then the basic brick was duplicated in order to create the two-brick model with all the interface elements required for simulation. Lastly, the two-brick model was replicated in horizontal and vertical direction in order to achieve the required dimensions of 1.2 x 1.2 m. In this modelling strategy, the material in the bricks and brick crack interface were kept as linear indicating that the cracks would be developed only in the mortar joints (as it was clearly seen during the experimental stage of the campaign). In order to effectively apply the load and to simulate the shear behavior of masonry, the bottom edges of the model were constrained in horizontal and vertical direction, whereas for the top edges, only for vertical direction. Additionally, in order to prevent horizontal deformation of the upper edge, a multi-point constraint was applied.

The loading consists of application of a unit horizontal displacement along the top of the panel which would be transferred uniformly along the entire upper edge due to the multi-point constraint applied earlier (Figure 5Figur). The strengthened panels were modelled using an additional reinforcement layer made of a reinforcement grid

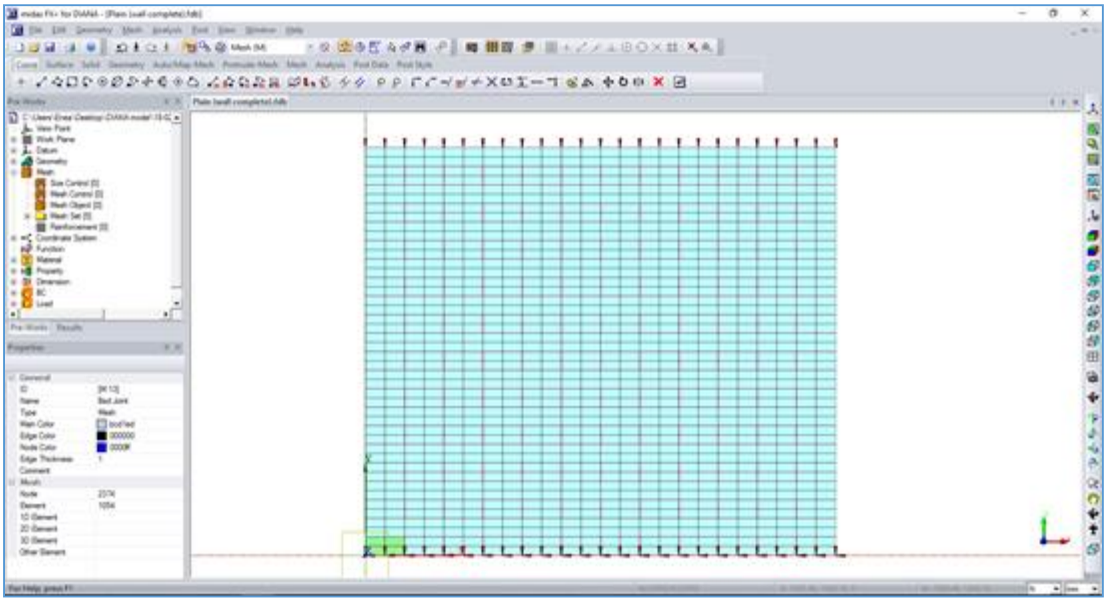

Figure 5. The finished model in midas FX+ for DIANA.

EXPERIMENTAL RESULTS

The main outcome of the experimental results was the type of failure mode for both types of panels: plain and reinforced, shear stress-strain diagrams and maximum shear stress and ultimate drift. The experimental results showed that all the tested specimens presented a similar failure mode, mainly characterized by a step-like crack along one of the diagonals.

The plain wall panels had a similar failure mode; it was observed that cracking occurred along the compressed diagonal, predominantly through the mortar joints. Nevertheless, in some cases, sliding along the mortar bed joints, following by diagonally extended cracks was observed (Figure 6). The overall failure mode can be categorized as tension failure followed by shear-sliding along the compressed diagonal in a step-like pattern.

The plain panels (W-06, W-07, W-08) exhibited similar failure modes; a step-like pattern along the compressed diagonal. The cracks occurred in the mortar joints.

Figure 6. Failure mode of plain, ferrocement strengthened and repaired panels.

Ferrocement jacketing reinforced panels (W-X-FC)

In the ferrocement jacketing reinforcement panels while loading, hair-like cracks were observed, mainly in the compressed diagonal. From the tests, it was observed no splitting in the head or bed joints. The total failure of the wall after the reinforcing ferrocement-plastering layer yielded, is attributed to the loss of bond between the plastering layer and the wall (Figure 6). The connection failure is the main cause of loss of adhesion of the strengthening layer that caused the overall failure of the panels.

In W-11-FC apart from the diagonal and hair-like cracks that were developed in the plaster layer, after exceeding the materials' resisting capacities, due to high tensile stresses, connection failure was observed, which resulted in thick radial cracks around the unloaded upper and bottom edges of the panel. In W-12-FC, connection failure resulted in debonding of the mesh reinforced plaster layer.

Despite the various final cracks of the panels, it was observed that the reinforcing layer had quite a satisfactory behaviour with respect to the strengthened panel. Until the ultimate strength was reached, no debonding of the mesh and wall panel was observed. For such a composite structure, made of heterogeneous and anisotropic material, the most important properties are ductility and shear strength, thus, in such a case, the performance of this technique is deemed successful.

Repaired walls with Ferrocement jacketing (W-X-R-FC)

The crack pattern of the ferrocement jacketing repaired panels of both series were similar to the corresponding W-FC reinforced panels. Before failure, after unloading, the diagonal cracks were not visible to the naked eye. Because of this reason, during testing stage, all the developed cracks were marked with a graphite pencil at various loading stages. Apart from the usual cracking mode, debonding of the repairing plaster layer was observed.

Shear stress-strain response

The shear stress-strain response is presented in Figure 7. For all the wall panels, the experimental curve was approximately linear prior to crack initiation, followed by a nonlinear portion of the curve up to the maximum strength. This similar behaviour was also observed in other studies [20-24].

As it can be seen, the plain wall panels of both are very brittle, and the stress-strain response is very short. The change in stiffness was observed usually for load values close to the ultimate load, as the first crack develops but it cannot expand due to the presence of the external reinforcement.

For the reinforced panels, on the other hand, stress-strain curve starts with a steep slope indicating the linear stage of masonry, whereas the second stage indicates the plastic phase and it is almost horizontal that usually started after the cracks became visible to naked eye. In this stage, the degraded stiffness can be observed (Figure 7).

From the stress-strain diagrams of the ferrocement jacketing repaired panels compared to their homologous pre-cracked panel. As it may be seen from the graphs, after repair, there is a considerable improvement of ductility and shear strength of the repaired panels.

Mechanical parameters

For the plain panels, the average shear strength was 0.337 MPa, with a maximum value of 0.423 MPa occurring at W-06 and a minimum value of 0.282 MPa occurring at W-07. Another parameter to be taken into consideration while analysing the behaviour of URM is the ultimate drift and ductility. The average drift was calculated to be 0.103%, with a maximum value of 0.150% occurring at W-07 and a minimum of 0.078% occurring at W-08. The average shear and elastic moduli were 365 and 912 MPa, respectively.

The panels reinforced with ferrocement jacketing resulted in maximum shear strength of 0.892 MPa (at W-10-FC) and a drift of 0.890% (at W-12-FC). As it may be seen from Table 4, average shear strength was 2.439 times higher than the plain panel, whereas the ultimate drift was 6.718 times higher. The average shear and elastic moduli were 126 and 315 MPa, respectively.

The repaired panels with ferrocement jacketing exhibited considerable improvement of shear strength and ultimate drifts when compared to their plain counterparts. The average values of ultimate diagonal load, shear strength and ultimate drift are 255.743 kN, 0.603 MPa and 1.366%, respectively. The maximum ultimate load and shear strengths were achieved from W-06-R-FC (288.956 kN and 0.681 MPa), whereas the minimum values were recorded from W-

07-R-FC (209.244 kN and 0.493 MPa). Nevertheless, W-07-R-FC achieved the highest ultimate drift of 2.229%.

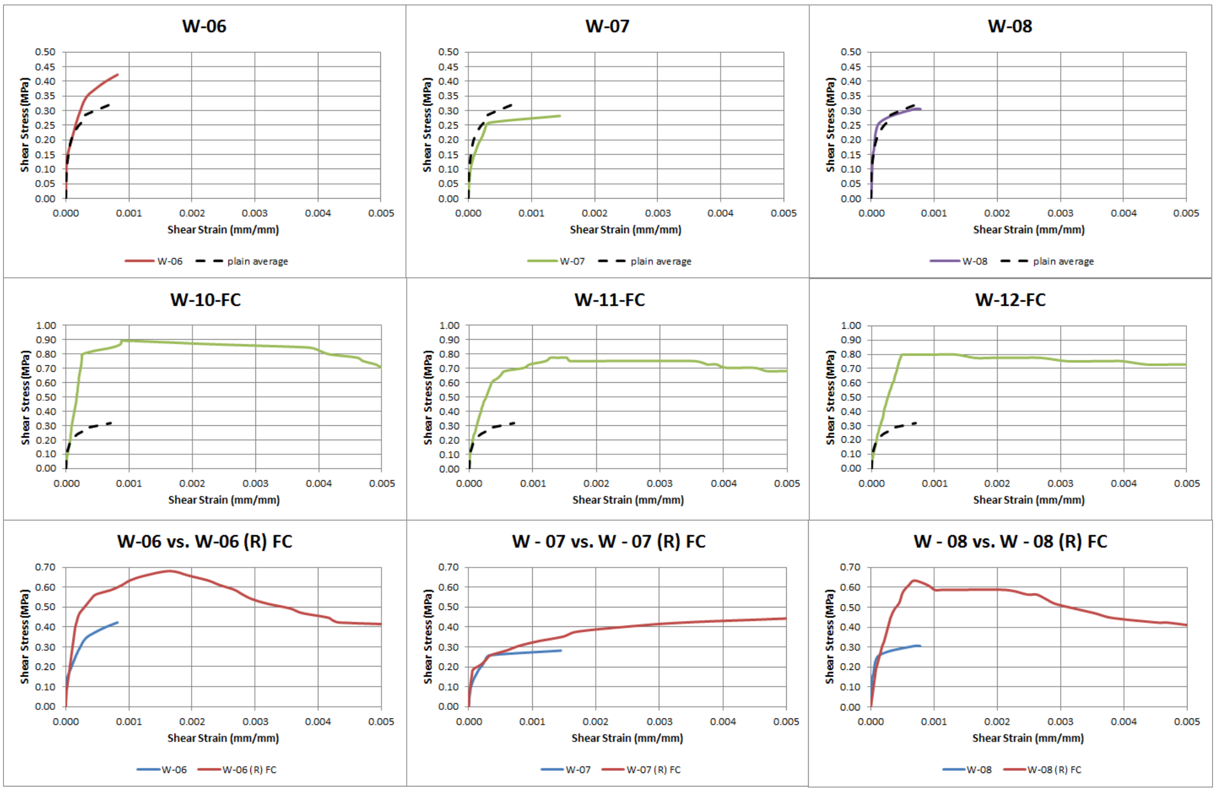

Figure 7. Summary of shear stress vs. shear strain of plain, ferrocement jacketing reinforced and repaired panels.

Table 4. Summary of mechanical parameters of tested specimen.

Wall panel	***P_{max} (kN)***	***v_{max} (MPa)***	***v_{max}/v_0***	***δ_u (%)***	***δ_u/δ_0***	***G (MPa)***	***E (MPa)***
W-06	179.352	0.423		0.082		515.488	1288.720
W-07	119.568	0.282		0.150		187.880	469.700
W-08	129.532	0.305		0.078		391.359	978.397
W-X	**142.817**	**0.337**	**-**	**0.103**	**-**	**364.909**	**912.272**
W-10-FC	378.632	0.892		0.512		174.238	435.596
W-11-FC	328.812	0.775		0.675		114.800	287.000
W-12-FC	338.776	0.798		0.890		89.708	224.270
W-X-FC	**348.740**	**0.822**	**2.439**	**0.692**	**6.718**	**126.249**	**315.622**
W-06-R-FC	288.956	0.681	1.610	1.075	13.110	63.346	158.365
W-07-R-FC	209.244	0.493	1.748	2.229	14.860	22.123	55.307
W-08-R-FC	269.028	0.634	2.079	0.794	10.179	79.864	199.660
(W-X-R-FC)	**255.743**	**0.603**	**1.789**	**1.366**	**13.262**	**55.111**	**137.777**

P_{max}- ultimate load, **v_{max}** – ultimate shear strength, **δ_u** – ultimate drift, **G**-shear modulus, **E**- Modulus of Elasticity

Experimental vs Numerical comparisons

In this section a comparison between experimental and numerical results is discussed. The main parameter that was used to understand the trend of the behavior of the panels is the comparison between stress-strain diagrams. The stress-strain diagram obtained after nonlinear analysis showed that the plain panels, as expected exhibited a very brittle behavior and much lower values in both analyses; 0.228 MPa shear strength and a maximum strain of 0.0012.

The ferrocement strengthened specimens achieved the highest shear stress of 0.937 MPa and a maximum strain of 0.0050, considerably higher than other two panels.

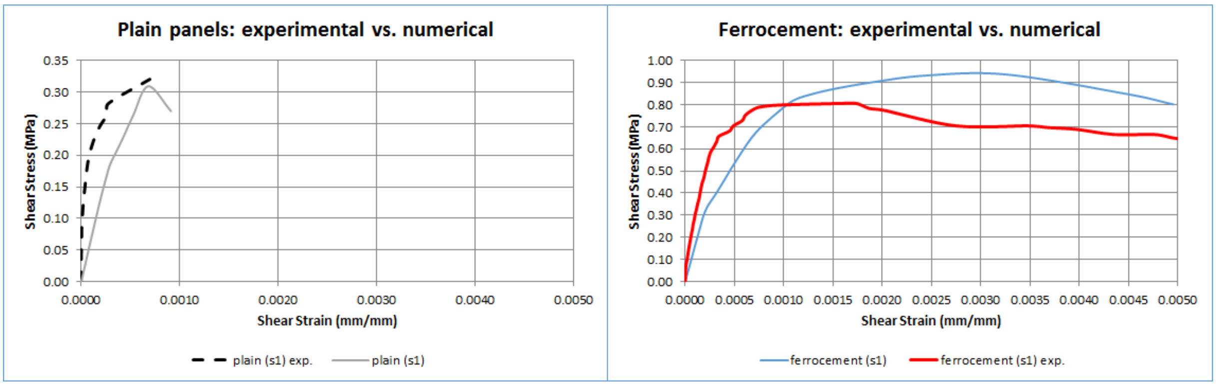

Figure 8. Comparison between experimental and numerical results of plain and ferrocement strengthened panels.

In Figure 8 it is presented the individual comparison between each of the investigated panel types. It was observed that all the modelled panels were more ductile. It may be explained by the linearity assumptions of assumed the material properties used for modelling.

CONCLUSION

In this paper nine diagonal compression tests were performed, three on plain panels and three on ferrocement jacketing reinforced panels to observe the structural behaviour of masonry and investigate the performance of ferrocement jacketing technique. Diagonal cracking was observed to be the main failure mode for both types of the specimen. The unreinforced walls exhibited a very brittle behaviour and low shear strength. The reinforced panels, on the other hand, demonstrated a much ductile behaviour, large deformation capacity and higher shear strength. This strengthening technique was proven to be an effective way to improve the overall structural performance of URM walls.

Acknowledgement

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