Polypropylene reinforced mortar coating for improvement of unreinforced masonry (URM) shear resistance

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ABSTRACT

This paper describes an experimental program for improvement of the shear resistance of unreinforced masonry (URM) by plastering with two layers of short polypropylene fibers (fiber length = 12 mm) embedded into a cementitious matrix under in-plane loading. Six diagonal compression tests as of ASTM E519-02, were carried out on masonry panels of dimensions 1.2 x 1.2 x 0.25 m built and tested at the laboratory. The main mechanical parameters such as the shear strength, modulus of rigidity and ductility were assessed and compared before and after strengthening. Additionally, the panels were also modelled using discrete micro-modelling using DIANA 9.6 and a non-linear analysis was conducted.

The results showed that polypropylene reinforced mortar coating increased the in-plane capacity of the unreinforced masonry by 270%.

Keywords: *polypropylene fibers, masonry retrofitting, URM, diagonal compression test*

INTRODUCTION

Masonry is one of the most used construction types in the world. Traditional stone or brick masonry load bearing walls were designed to resist only gravitational loads, or even worse, have not been designed at all, but simply realized by the rules of common practice [1].

Unreinforced masonry (URM) structures have proven to be more susceptible to damage due to lateral forces, especially seismic loads. Recent earthquakes around the world have shown that these types of structures are the ones that suffer more damage. As the out-of-plane failure of URM walls can be restrained by improving connections and reinforcing the weakest structural elements, it is the in-plane capacity of the walls, especially the shear resistance that governs their behavior. For this reason, it is important that the strengthening strategies to be focused on improvement of shear strength and increasing ductility.

Over the years, several strengthening techniques such as i) filling cracks by grouting; ii) stitching of large cracks with metallic or brick elements; iii) external or internal post-tensioning with steel ties; iv) shotcrete jacketing; v) ferrocement and vi) center core, textile reinforced mortar (TRM) and Fiber reinforced polymers (FRP) etc. have been developed aiming at improving these parameters to comply with the modern design codes and extend their service life [2-16].

MATERIALS AND METHODS

This study is focused on testing of three unreinforced and three reinforced 1.2 m x 1.2 m x 0.25 m panels under diagonal compression to simulate shear failure as of ASTM E 519 [18]. The diagonal compression test has been used by many researchers [2-17]. All the panels were built of two leaf English bond of new clay bricks with 15 mm-thick bed mortar joints of a volumetric mix ratio of Portland cement: lime: sand 1:1:6. The specimens were built and tested in place at EPOKA University Civil Engineering laboratory.

The reinforcement method consists of plastering of both sides of the panels using polypropylene fiber reinforced mortar of a 25 mm-thick layer of cement: sand mortar of a volumetric mix ratio of 1:4 and water/ cement ratio of 0.4 plus 2% of fibers in volume (Figure 1). The walls were left to cure for 28 days. Before testing, a layer of white paint was applied to better visualize the cracks during the tests. Characteristics of the polypropylene fibers are given in Table 1.

The specimens letter designation is: URM for unreinforced panels and PP for panels plastered with polypropylene reinforced mortar coating.

Figure 1. Polypropylene reinforced mortar coating of the URM panels.

Table 1. Technical specifications of polypropylene fibers used for the reinforcement.

Property	Value/Rating
Specific gravity (g/cm³)	0.91
Fiber length (mm)	12
Fiber diameter (μm)	18
Melt point (°C)	160
Ignition point (°C)	365
Thermal conductivity	Low
Electrical conductivity	Low
Specific surface area of the fiber (m^2/kg)	250
Acid resistance	High
Alkali resistance (%)	100
Tensile strength (MPa)	300–400
Young’s modulus (MPa)	4000

Test Set-up

The testing procedure is done according to ASTM E 519-02 standard [18]. It consists of application of a diagonal compression load exerted by a hydraulic jack which compresses the wall diagonally, providing the desired failure mode; diagonal cracking and/or bed joint sliding failure (Figure 2).

Figure 2. Diagonal compression test set-up.

The calculation procedure is as follows:

$$S_s = \frac{0.707P}{A_n} \qquad \text{(Equation 1)}$$

where: S_s – shear stress (MPa); P – load exerted along the compression diagonal (N); A_n – net area of the specimen (mm^2);

$$A_n = \frac{w+h}{2} t \cdot n \qquad \text{(Equation 2)}$$

where: w – width of specimen (mm); h – height of specimen (mm); t – total thickness of specimen (mm); n - percent of the gross area of the unit that is solid, expressed as a decimal.

$$\gamma = \frac{\Delta V + \Delta H}{g} \qquad \text{(Equation 3)}$$

where: γ - shearing strain (mm/mm); ΔV– vertical shortening (mm); ΔH – horizontal extension; g – vertical gage length.

$$G = \frac{S_n}{\gamma} \qquad \text{(Equation 4)}$$

where: G - modulus of rigidity, MPa

Finite Element Modelling

Apart from experimental test, the specimens were modelled adopting the simplified micro-modelling approach for modelling of masonry in midas FX+ for DIANA 9.6 suggested by Zijl et al. [19] (Figure 3). The “Simplified Modelling Method with Brick Crack Interface” consists of having the bricks and mortar are modelled separately as two different materials using the following elements: for bricks Q8MEM element [20]. The modelling procedure and the input parameters are carried out in-depth from another study of the authors [21].

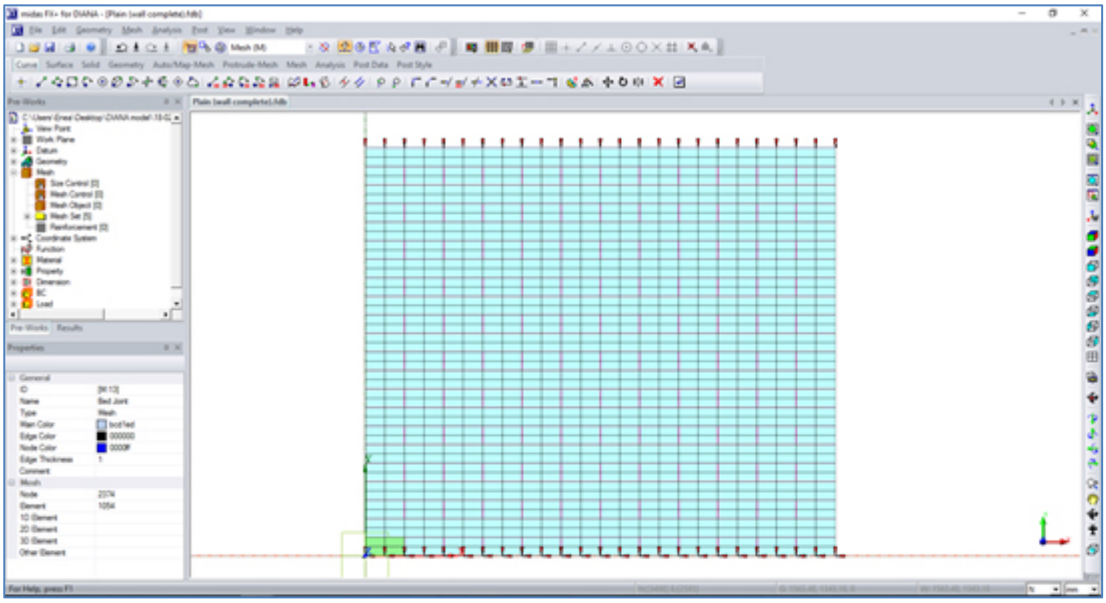

Figure 3. The finished model in midas FX+ for DIANA.

RESULTS AND DISCUSSION

The main results obtained from the experiments were the mode of failure mode for each panel, shear stress-strain diagrams, maximum shear resistance and the ultimate drift. Before testing, the individual characteristic strengths of mortar, brick and masonry assemblage was determined. For the bricks, the compressive strength was 24.03 MPa and the flexural strength 4.53 MPa. The mortar used for the construction of the walls had a compressive and flexural strength of 5.32 and 0.55 MPa, respectively. On the other hand, the reinforced plastering layer’s compressive and flexural strengths were 17.64 and 2.12 MPa, respectively.

Failure mode

All the panels exhibited a similar failure. The overall failure mode of both types could be categorized as in-plane shear failure; a step-like crack developed along the loaded diagonal through the mortar joints (Figure 4 and Figure 5). The main crack started from the center of the wall panel and propagated along the mortar joints toward the panel's corners. The formation of the shear crack, i.e., the failure, was sudden, and all the panels exhibited a very brittle behavior. In the reinforced panels, the diagonal crack was deeper and wider, followed by smaller parallel cracks. The behavior of all the six panels was brittle.

Figure 4. Failure mode of the unreinforced panels.

Figure 5. Failure mode of the reinforced panels.

Shear stress-strain response

The shear stress versus shear strain response of all panels was determined by calculating the shear stress and the angular strain using Equations (1) and (3), respectively. For the URM panels, the relationship was approximately linear before the crack initiation, followed by a nonlinear response up to the maximum shear capacity. The panels exhibited little deformation before the sudden drop in their resistance, thus losing almost all of the load-carrying capacity. As it is seen in Figure 6, both shear resistance and deformation capacities are limited.

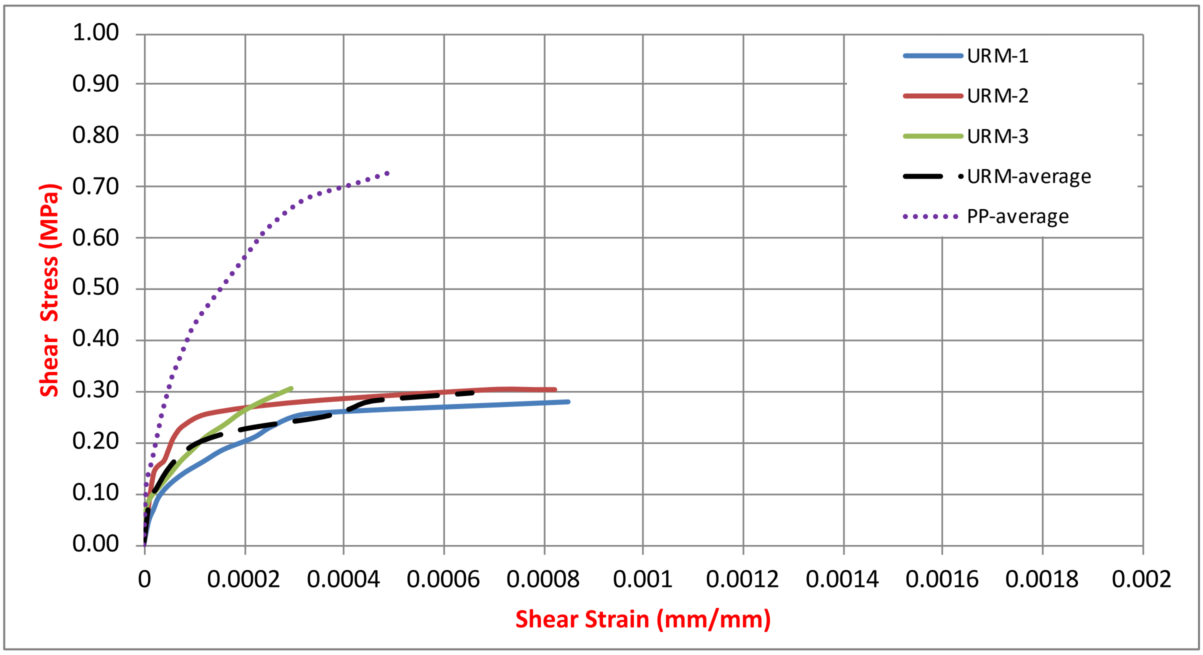

Figure 6. Shear stress-strain relationship of the URM panels.

For the PP reinforced panels, a similar behavior was observed. The stress-strain response of polypropylene strengthened panels is short (Figure 7), indicating a brittle behavior of the panels. Nevertheless, the shear strength is observed to be considerably higher when compared to the URM panels.

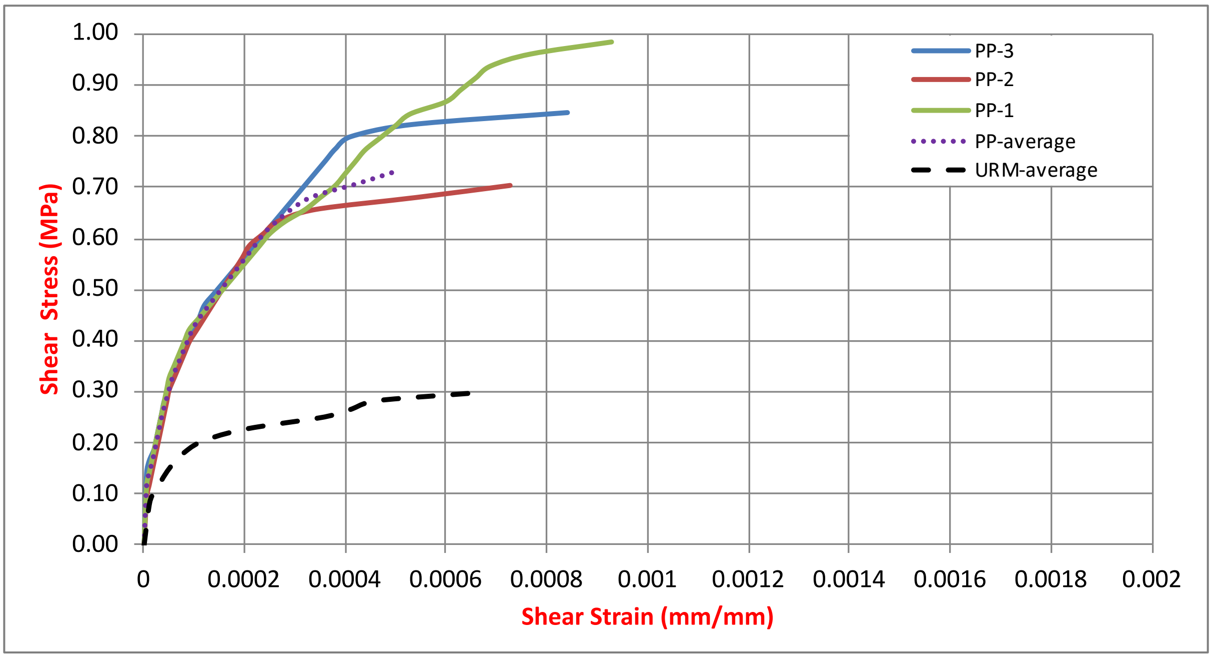

Figure 7. Shear stress-strain relationship of the PP panels.

Mechanical Parameters

A summary of all the mechanical parameters of the six tested specimens is presented in Table 2. The URM panels failed at an ultimate load ranging between 119 and149 kN. The average shear strength was 0.413 MPa, with a maximum value of 0.352 MPa occurring at URM-3 and a minimum value of 0.282

MPa occurring at URM-1. The average drift was calculated to be 0.104%, with a maximum value of 0.150% occurring at URM-1 and a minimum of 0.078% occurring at URM-2.

The PP reinforced panels failed at much higher loads but exhibited a brittle behavior. The ultimate load varies from 298 to418 kN. The average shear resistance was 0.845 MPa, with a maximum value of 0.986 MPa occurring at PP-1 and a minimum of 0.704 MPa, at PP-2. The average drift was recorded to be 0.084%.

Table 2. Summary of mechanical parameters of tested specimen.

Wall panel	P_{max} (kN)	ν_{max} (MPa)	δ_u (%)	G (MPa)	E (MPa)
URM-1	119.5	0.282	0.150	188	470
URM-2	129.5	0.305	0.078	392	978
URM-3	149.4	0.352	0.083	424	1060
URM-average	132.8	0.313	0.104	335	836
PP-1	418.4	0.986	0.096	1027	2568
PP-2	298.9	0.704	0.072	971	2429
PP-3	358.7	0.845	0.084	1006	2515
PP-average	358.7	0.845	0.084	1001	2504

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

Comparison experimental vs. numerical

The main parameter that was used to assess the structural behavior of the panels is the comparison between stress-strain diagrams described in Figure 8.

The stress-strain diagram obtained after nonlinear analysis showed that the polypropylene reinforced panels exhibited similar behavior in both cases; high shear stress (0.845 MPa) but a very low shear strain value (0.0084), and in the numerical analysis a shear strength of 0.679 MPa and a maximum strain of 0.0013.

Plain panels, as expected showed a very brittle behavior and much lower values in both analyses; 0.228 MPa shear strength and a maximum strain of 0.0012.

Numerical analysis, even though based on several assumptions, provided good insights of the behavior of the panels during linear and nonlinear analysis. The aim of the analysis was to compare the experimental results with a previously done and well-established numerical procedures.

From the shear stress-strain curves, it is observed a good fit of the numerical model versus the experimental results.

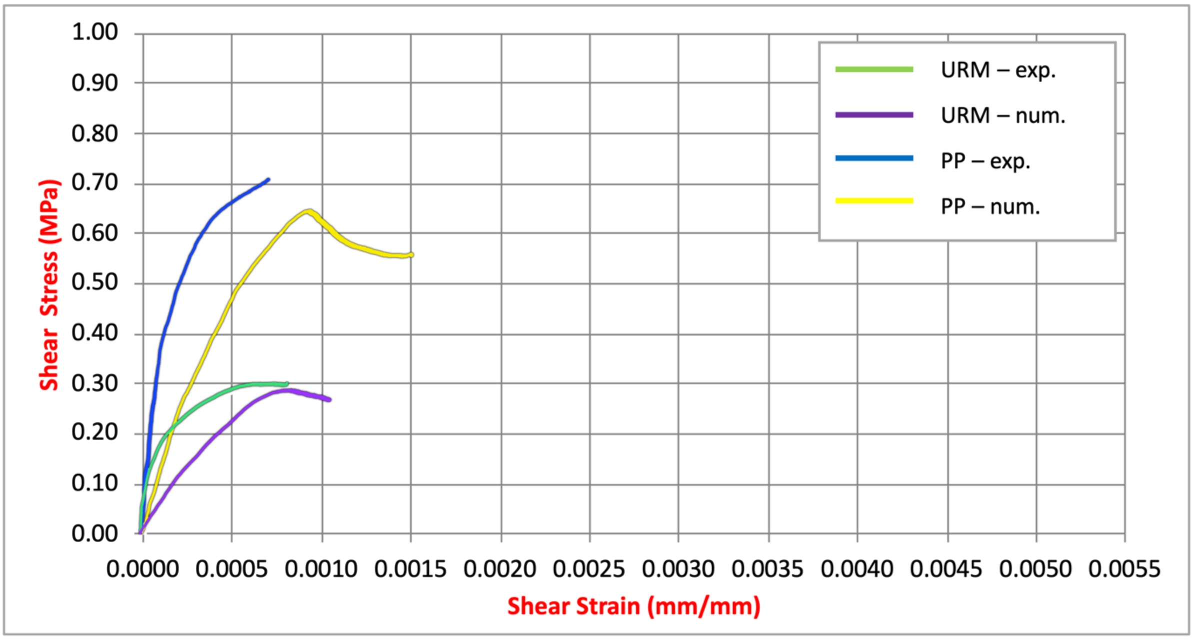

Figure 8. Comparison between experimental and numerical shear stress-strain relationship of URM and PP.

CONCLUSIONS

In this paper, the test results of an experimental investigation on brickwork shear walls that were strengthened with polypropylene fibers embedded into a cementitious matrix have been presented. The use of polypropylene to reinforce brickwork walls was ultimately effective.

The maximum increase in the in-plane load-capacity was achieved when two jacketing coatings were used as a retrofitting method: the shear capacity increment was 270% when compared to the unreinforced wall panels. Despite the improvement of the shear strength, the ductility of the reinforced panels remained limited.

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