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Shear strengthening of unreinforced masonry wall with different fiber reinforced mortar jacketing

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HIGHLIGHTS

- We tested 12 masonry wall panels under diagonal shear load.
- Three different fiber reinforced mortar used four different ways to strengthening.
- Application of fiber reinforced mortar improves shear strength of the wall panels.
- Ferrocement and polypropylene reinforcement improved shear strength significantly.
- The strengthening techniques need connection to utilize benefit of the reinforcement.

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ABSTRACT

This study presents the comparison of different strengthening techniques for unreinforced masonry walls. Three materials are considered in four different ways for strengthening URM walls, textile reinforced mortars (TRM) plastering, applied on one and both faces of the wall, polypropylene fiber reinforced mortar plastering (PP-FRM), and ferrocement reinforced mortar plastering. Shear performance of the strengthened walls were tested under diagonal compression test method. Changes of shear performance of strengthened walls were determined by comparison of before and after the application of the reinforcements. The walls reinforced with ferrocement and polypropylene mortar plaster exhibited a significant improvement in shear strength capacity of up to 412% when compared to the control specimen. The results indicate a good increase of shear strength for all selected strengthening techniques, while stiffness change and failure mode are more varied.

1. Introduction

Masonry walls are composed of bricks and mortars, which have distinct properties. The adhesion provided by mortar between these constituents is responsible for the behavior of masonry under lateral loads. Therefore, masonry is very vulnerable when subjected to earthquake loads. Unreinforced masonry (URM) buildings are constructed with thick bearing masonry walls in box-like structures form. These walls are main load carrying elements which can safely carry vertical loads without damages. However the shear response of masonry walls is more complex and depends on composite nature of mortar and bricks. Furthermore, the stocky nature of URM walls and the zero tensile strength of the material, makes masonry very brittle and with low ductility [1].

The Darfield and Christchurch earthquakes that stroke New Zealand provide a vast amount of examples of damages to URM from earthquakes. The damages are categorized as non-structural and structural. The non-structural damages include chimney and parapet failure, veneer peel-off, gable wall out-of-plane failure. The structural damages include out-of-plane wall failure, and in-plane wall failure. The in-plane wall failures observed were the diagonal shear cracking in piers, spandrels and walls; sliding shear on mortar bed joints or between stories; and in-plane rocking or toe crushing [2,3]. Most of the URM buildings were built based on experience and construction practice of the time it was built. Moreover many of them were designed and built before any code or provisions for seismic load were required. Therefore URM buildings need strengthening to satisfy today codes requirements and engineering understanding of URM.

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Due to the huge building stock of URM throughout the world and weak characteristic under seismic loads, strengthening techniques for masonry have evolved significantly last two decades. Originally, the techniques used for RC structures were adopted for masonry structures as well. These comprise bracing, shear wall addition, secondary moment or bracing frames (RC or steel) [4]. Typical masonry strengthening techniques comprise restoration techniques such as grout injection, crack stitching and repointing [5]. New techniques have risen the recent years, such as post-tensioning, base-isolation, shotcreting and jacketing [6]. While the classical solutions such as bracing and shear wall addition are appropriate when the structural system presents deficiencies; grouting, and stitching can only close cracks and restore the wall capacity at a certain degree, jacketing is a local strengthening technique that seems very promising.

The development of new materials such as fiber polymers has made jacketing a solution for strengthening structural elements. Fiber reinforced polymer (FRP) wrapping of masonry walls has been tested in a variety of configurations. Besides for the conventional form of FRP used in strengthening of RC element, textile reinforced mortar (TRM) has been developed specifically for masonry. It consists of glass fibers pre-embedded in epoxy, and woven in the form of mesh. It has lower modulus of elasticity than CFRP, therefore is more adequate for the strengthening of masonry walls [7]. The application of TRM increases the shear strength of masonry walls. It also affects the stiffness and ductility, and improves the failure mode. The walls have a gradual prolonged failure, which is highly desirable in earthquake prone areas [8]. The application of TRM on one side of the wall, due to the asymmetry of the section and mix failure mode, has resulted less satisfactory. The plain side has excessive deformations. This strengthening technique not always results in increase in stiffness of the walls [9].

Ferrocement jacketing has also been tested in masonry walls. This strengthening technique results in considerable increase in stiffness. Studies have indicated that strengthening of predamaged masonry walls with ferrocement jacketing can restore the original capacity and original stiffness of the wall. In the case of ferrocement jacketing, a key point in the success of the strengthening is the use of anchorages to fix the jacket and prevent it from delamination [10]. Ferrocement has high flexural and shear strength, and can control the crack formation. Therefore it gives good results when used as a strengthening technique for masonry. Masonry columns have been confined with ferrocement layers, which has restored and/or increased the capacity of the column [11,12]. Further studies have tested the effectiveness of ferrocement for the confinement of masonry walls. The jacket increases the strength and improves the ductility and failure mode of the walls [13]. A comparative study on the shear strength of masonry walls retrofitted with various techniques, including ferrocement shows that it increases the shear strength and the stiffness of the wall considerably [14]. Other advantages in the use of ferrocement as strengthening material are the availability of the galvanized steel wire mesh and the unskilled workmanship required to install it.

Strengthening masonry walls with fiber reinforced mortars (FRM), which are microfibers embedded in mortar, is a technique needs to be study. The microfibers can be of different composition: steel, glass, synthetic fibers (acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene) and natural fibers (straw, coconut, bamboo). The addition of these fibers to concrete/mortar affects its flexural and shear properties, the energy absorption capacity and delays cracking [15]. Polypropylene fibers are chemically inert fibers that bond mechanically with the mortar through the contact area. In order to obtain good bonding between the fibers and the mortar smaller diameter fibers are produced. The dimensions of the fibers range between 7 and 77 mm, and the aspect ratios are in the range 20–100. These fibers are usually used to plaster tunnel walls, due to the high resistance to impact loads and the good cracking behavior. The most usage of polypropylene for strengthening masonry walls is in the form of meshes. The research on this topic has shown that polypropylene meshes plastered to masonry walls improve their post crack behavior, and restore the capacity of damaged walls [16]. Other studies found out that polypropylene meshes do not enhance the shear strength of the walls [17]. Affect of polypropylene microfibers to mortars is known to increase the energy absorption and toughness, limits cracking due to the spread of the fibers, which hold the matrix together, improves the flexural and shear strength, but does not affect the compressive strength of mortars [14]. Mortar mix with the polypropylene microfibers, ferrocement and TRM one and two sides plaster are used in this study to strength unreinforced masonry walls. Comparison of different strengthening technique is carried out by diagonal shear test.

2. Materials and methods

The critical seismic strength for masonry is the shear strength. Usually, masonry sections do not present problems for axial loads, but have limited capacity in shear. To investigate the behavior of strengthened walls under lateral loading, the diagonal shear test, standardized by ASTM 519 [15] was used. For the study, 12 walls were constructed, 2 in full scale, as defined by ASTM 519, and the rest as half-scale. The size of standard walls was 1.2 × 1.2 m while the size of half-scale walls was 0.65 × 0.65 m. The thickness for all walls was 0.25 cm.

Two layers of wire mesh are used for each side of the wall. The two layers are tied together by means of a thin wire. Surface preparation is required in order to install the steel wire meshes. The anchors used, were normal threaded bolts of diameter 6 mm .Welded steel wire mesh of opening size 12.7 mm 12.7 mm with an average wire diameter of 1.1 mm was used.

The test setup consisted of the loading frame, two steel loading shoes, a hydraulic jack and two dial gauges for the small and half-scale walls. Since the standard size walls were too big to be moved with ease, a modification was done to the test setup. Instead of the loading frame, the two loading shoes were fixed by means of 4 steel rods, riveted on both ends (Fig. 1a). The load was applied by means of the hydraulic jack at small increments to allow for the detection of cracks prior to failure. Fig. 1 shows the ASTM test setup, and the adopted setups for the standard size and half-scale specimens (Fig. 1b).

In this study, the 2 full size walls were tested plain, with no strengthening or any form of plaster. From the half-scale walls specimens, 2 were tested plain, 2 were strengthened with TRM jacketing in only one side, 2 were strengthened with TRM on both sides, 2 were strengthened with ferrocement jacketing, and 2 were strengthened with polypropylene FRM jacket. The specimens are named as PL (plain-large), PS (plain-small), TI (TRM-one side), TII (TRM-two sides), FC (ferrocement) and PP (polypropylene).

The shear strength and shear modulus of the specimens were calculated using ASTM [18] recommended Equations

$$S_n = \frac{0.707P}{A_n} \tag{1}$$

(a) standard size specimen setup **(b) half-scale specimen setup**

Fig. 1. Test setup for diagonal shear test.

$$A_n = \frac{w + l}{2} tn \quad (2)$$

$$\gamma = \frac{\Delta V + \Delta H}{g} \quad (3)$$

$$G = \frac{S_n}{\gamma} \quad (4)$$

where:

S_n – shear stress; P – load exerted along the compression diagonal; A_n – net area of the specimen; w – width of specimen; h – height of specimen; t – total thickness of specimen; ΔV – vertical shortening; ΔH – horizontal extension; g – vertical gage length.

3. Strengthening masonry walls

The fibers that were used for strengthening the URM walls in this study are glass fibers SikaWrap 350G Grid [18], pre-embedded in epoxy. This material has been specifically designed for strengthening of masonry walls. The fiber was fixed to the wall by means of a special type of mortar SikaMonoTop 722 [7], SIKA. The TRM nets were cut to fit the size of the walls. The mortar was prepared by mixing the Mono Top mortar with water at 20–21% in mass of the mortar mixture. Since the pot life of this special mortar is 30–45 min, small portions of mix were prepared at a time. Then, a thin first layer of mortar was applied on the surface of the walls. The net was placed and embedded on the first layer, and covered with a second layer of mortar, which also fixed the net on the wall face (Fig. 2a). The walls were left to cure in environment conditions for 28 days. This strengthening was used for one and two sides of the masonry wallet specimens.

The ferrocement jacket consists of a galvanized steel mesh that was attached to the wall and worked as an external reinforcement to the wall. The mesh was fixed to the wall by means of mechanical anchors and common mortar. The steel wire mesh was cut equal to the walls' dimensions, 650 × 650 mm. Two layers of wire mesh were used for each side of the wall. Surface preparation was required in order to install the steel wire meshes. Anchors are needed to be placed at certain distances, at least every 30 cm [19]. For more versatility of work and application, threaded bolts of diameter 8 mm and length 70 mm were used as anchors. Holes were preliminary drilled every 30 cm on both sides of the wall. Then, the wire meshes were placed on the faces and the anchors were fixed with care, in order not to break the bricks due to the extra stresses that come when threading. Afterwards, the walls were plastered on both sides with approximately 2–2.5 cm mortar (Fig. 2b). The ratio cement/sand used is 1:4, and the water content is 0.4 (W/C).

The last strengthening method is using polypropylene fiber mixed with plastering mortar. The walls were jacketed on both sides with 2–2.5 cm thick plaster that contains certain amounts of polypropylene fibers. The suggested percentage that does not affect the workability and does enhance the properties of the FRM is 1–2%, commonly used the value of 1.5% [15,20]. A commonly used mortar mix design for practical applications of FRM (mainly tunneling) consists of 1 portion cement and 4 portions of aggregate (both fine and coarse). This ratio yields FRM with very low workability. Therefore, the mortar produced for better workability with 1 portion sand, 1 portion cement, 0.5 (W/C) and 1.5% of fibers by volume. The fibers were dry mixed with the sand and the cement, and water was added in the end. The FRM was applied on both sides of the wall (Fig. 2c).

(a) Application of TRM strengthening to masonry walls

(b) Application of Ferrocement strengthening of masonry walls

(c) Application of PP-FRM strengthening of masonry walls

Fig. 2. Application of strengthening to masonry walls (a) TRM; (b) ferrocement; (c) PP-FRM.

4. Results and discussions

The masonry walls were tested in diagonal compression to check the efficiency of the selected strengthening techniques. The load increments and corresponding deformations for both diagonals were recorded. Fig. 3 presents the stress–strain curves for all tested walls.

The test on the plain walls, both standard size and half-scale revealed similar failure mode. The behavior of the walls is brittle; the failure is sudden, with no considerable crack development prior to failure. The main crack pattern follows the bed and head joints across the compressed diagonal. Fig. 4 shows the failure mode of the both types plain walls.

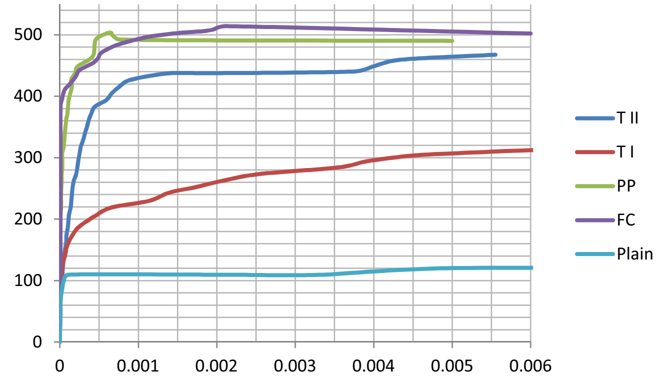

Fig. 3. Stress–strain curves for tested masonry walls.

At first loading steps the specimens carried load without significant damages or cracks. The failure load corresponds to the formation of the visible crack also. The cracks formed on both specimens were stepped along the compressed diagonal, which is the expected failure. The cracks in the second specimen follow a more diagonal pattern than the crack in the first specimen. Failure of full specimens is shown in Fig. 4a, with the main crack starting at the loading corner and continuing along the diagonal through the mortar joints. Correlation between full and half size test samples were left to researcher by ASTM [16] and out of scope of this study. However compressive study for the correlation for several different sizes was carried out earlier [21].

The small walls fail in a similar fashion with the large plain walls. At first, no significant deformations take place in any of the two diagonals. Then, the crack initiates below the third course of bricks, developing along the compressed diagonal and the failure is suddenly occurs. The failure occurs along the bed/head joints, but the integrity of the rest of the wall is preserved. The crack pattern is similar in both walls. The failure of second specimen is shown in Fig. 4b. Similarly to the full scale specimens, both walls display a similar behavior. Stress train curve of the specimens start with a stepwise slope, which corresponds to the linear stage. The second portion of the curve is almost straight, horizontal and corresponds to the plastic phase. This stage is initiated after the significant (visible) cracks are formed, and thus represents the degraded stiffness of the walls.

The strengthened walls fail in a more ductile manner. In all cases fine cracks start to develop in the strengthening jacket. After the cracks have widened sufficiently to cause the failure of the jacket, the load is carried out by the wall, and cracks appear along the mortar joints. First TRM (TII) reinforced walls were tested under diagonal compression load. First cracks develop along the compressed diagonal of plastered surface of the specimen (Fig. 5). As the load increased, the cracks widened. The glass fiber net has yielded but it still holds the jacket together. Afterwards, the TRM-jacket was disconnected from the wall, which led to the transfer of the entire load to the wall itself. The increase in diagonal load carrying capacity of the TII two-sided strengthened wall is almost three times of the half size plain specimen. The glass fibers improve the deformation capacity as well. The behavior of both specimens is similar and they are characterized by similar stiffness and ultimate strengths. The failure of the specimens were took place after an excessive cracking and de-bonding of the reinforced plaster (Fig. 5b).

The strengthening configuration of TI yielded the lowest results in diagonal load carrying and deformation capacity. As the wall was strengthened in only one side, the section was not symmetric anymore. There was an increase in stiffness in one side of the wall, while the other side behaved as a plain wall. The plain side started to deform and crack at low levels of load, while the strengthened side didn't show any cracking. Afterwards, the cracks appeared in the TRM side as well (Fig. 6a). The ultimate load is almost 1.6 times the failure load of the plain walls. The plain side had a failure similar to that of plain wall, in a stepped fashion cracks. At the same time, the wall bent out-of-plane due to the difference in stiffness between the two sides (Fig. 6b).

The ferrocement jacketed walls (FC) were carried highest ultimate diagonal load compared to others. Hair-like cracks start to develop along the compressed diagonal. At a load of 110–115 kN several cracks have formed along the diagonal strip and start to widen (Fig. 7a). There are no splits in the bed/head joints and the specimens were failed at ductile manner. At the ultimate load plaster starts disconnecting from the wall (Fig. 7b). The ductile behavior of the specimens wall were not only depended on the addition of the wire mesh, which works as act external reinforcement, thus providing the ductility and energy absorption plain masonry walls lack, but also the connection of the jacket to the wall. Even after the yield of the steel, the mesh still could carry load. Both the load capacity and the deformation capacity of the ferrocement jacketed wall increased considerably compared to plain specimens.

The polypropylene jacketed specimen (PP) shows similar behavior with FC specimen, at the diagonal load of 70–90 kN, the first cracks occurring along the compressed diagonal (Fig. 8a). As cracks continued to propagate, the jacket began to disconnect from

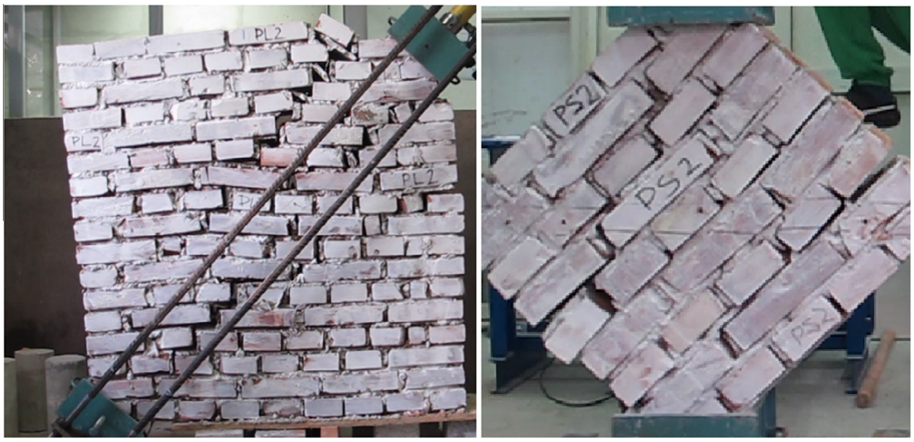

Fig. 4. Failure of plain specimens: crack development across the compressed diagonal; (a) standard size wall; (b) half-scale wall.

Fig. 5. TRM (TII) jacketed walls on both sides: (a) crack initiation along the compressed diagonal; (b) excessive cracking occurs and de-bonding.

Fig. 6. TRM jacketed walls on one side only (TI): (a) crack development on the strengthened side, (b) inward bending of the strengthened side while cracks are still minor.

Fig. 7. Ferrocement jacketed wall: (a) hair-like cracks developing along the compressed diagonal; (b) yield of the jacket and total failure of second specimen.

the wall at the ultimate load (Fig. 8b). The failure of the wall began in the third course of bricks, by splitting the bed/head joints. After that the jacket was disconnected from the wall, and the wall itself disintegrated. The shear strength of the PP was increased 400% compared to PS specimen capacity.

The comparison between the plain and strengthened walls reveals that the application of all the strengthening techniques increases the shear strength of the wall from 163.63% to 412.71% and shear modulus from 5.67% to 2240%. Only the TI1 specimen showed lower shear modulus, this is encountered in literature as well [18,22,23]. The shear strength and shear modulus are calculated from Eqs. (1)–(4) and presented in Table 1. The higher stiffness and shear strength belongs to ferrocement jacketed walls, followed by PP jacketed walls, TII, TI and in the end, plain specimens. PP jacket application was found as the easiest and practical to apply to any form of URM building. However mode of failure of the specimens showed that all the strengthening techniques need some form of connection to fully utilize benefit of the reinforced plaster until the ultimate stage.

5. Conclusions

In this study is presented an investigation on the efficiency of four strengthening techniques for URM walls. The techniques are TRM jacketing on one side of the walls, TRM jacketing on both sides of the walls, PP-FRM jacketing and ferrocement jacketing. An

Fig. 8. Polypropylene jacketed walls: (a) cracks developing; (b) major crack and failure of second specimen.

Table 1
The increase in shear strength and modulus due to the strengthening.

Specimen	Shear strength (kPa)	Pct. increase in shear (%)	Shear modulus (GPa)	Pct. increase in shear modulus (%)
PL (average)	140.4	–	0.742	
PS (average)	120.32	–	1.043	–
FC (average)	616.89	412.71	24.413	2240.65
PP (average)	603.77	401.80	3.946	278.33
TII (average)	481.26	300.00	1.841	76.51
TI1	314.2	163.63	0.640	−38.64
TI2	317.2	163.63	1.098	5.27

experimental program was designed and 12 walls were tested. From the conducted tests, the following conclusions can be drawn:

a. The plain masonry walls fail in the same manner, regardless of the size. Their failure is sudden and brittle, and the crack pattern is stepwise along the mortar joints.
b. The strengthened masonry walls have better behavior under diagonal shear strength test. Many hair-like cracks develop in the jacketed walls prior to failure. TRM walls jacketed on only one side of the wall exhibit the worst behavior. They undergo out-of-plane deformation, and significant cracks develop in the plain side, before cracks appear in the jacketed side.
c. The shear stiffness is considerably increased for ferrocement and PP jacketed walls, while walls strengthened on both sides with TRM show lower increase in shear modulus. Walls strengthened on only one side may experience little or no increase at all on stiffness, owning to the out-of-plane failure that occurs.
d. The main problem associated with TRM jacketing is the lack of anchors that could have provided better connection between the walls and the jackets. Instead, all the connection was carried out by the special mortars used for plastering of TRM walls.

Compliance with ethics guidelines

This section is intended for authors to declare compliance with ethical standards of the Journal Recommendations.

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