SHEAR STRENGTHENING OF URM CLAY WALLS WITH FRP SYSTEMS

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Abstract

This paper presents an experimental program dealing with the shear strengthening with FRP systems of URM walls built with concrete and clay units. Ten concrete and five day masonry panels, strengthened with FRP composites in the form of laminates and rods, and stainless steel, were loaded along the wall diagonal to observe their shear performance. The dimension of the concrete masonry panels was 1.625 x 1.625 m. having a thickness of 152 mm, the masonry units were 203x152x406 mm. The clay panels were 1.22x1.22x0.1 m and the masonry units were 102x203x64 mm. For the rods the Structural Repointing technique was used. This technique consists in placing FRP rods in the masonry bed joints. On the contrary, for laminates, the Manual Lay-Up technique was used.
The results demonstrated the effectiveness of FRP for increasing the shear performance of URM walls in terms of both capacity and pseudo-ductility.

1. Introduction

It's recognised that an infill URM wall can easily collapse when it's loaded with an In-Plane force. This happens because this type of load generates a shear stress and a shear failure, identifiable by the cracks along the diagonals. The wall capacity, now, is totally lost and the panel can fall even under a low Out-of-Plane load, endangering human lives.

It's possible to resolve part of this problem by the use of FRP systems. Many experimental works showed that it's possible to increase the ultimate capacity of a wall reinforcing it with FRP composites, without any addition in its weight and stiffness and avoiding dangerous consequences in case of seismic events. A main benefit is even the aesthetic and logistic advantage from the use of FRP: there is a minimal loss of usable space and with a plaster it's possible to hide the strengthening material.

2. Material characterization

Tests were concluded to characterize the mechanical properties of the materials used in this investigation. The average compressive strengths of masonry units resulted from the testing of prisms (ASTM C1314). The walls were strengthened with #2 GFRP bars having diameter of 6 mm, CFRP and GFRP laminates, stainless steel circular bars and internal steel nets. FRP and stainless steel bars were embedded into an epoxy-based paste and in a Latex Modified Cementitious Paste which, according to the manufactures and to test results (ASTM C–496–96), perform the mechanical properties as shown. All the properties are shown in Table 1:

Table 1. Material properties

Material	**Compressive strength [MPa]**	**Tensile strength [MPa]**	**Modulus of Elasticity [MPa]**
Concrete blocks	16.73	-	-
Clay bricks	15.78	-	-
#2 GFRP bars	-	824	50162
Stainless Steel bars	-	939	118917.7
Internal Steel net	-	625.6	204403.1
CFRP rect bars	-	1392.4	142735.9
CFRP laminates	-	27176	264000
GFRP laminates	-	1687	83129
Epoxy paste	86.18	27.58	3102
LMCP	1 day – 5.5 28 days – 34.5	1 day – 1.0 28 days – 4.5	2.8 x 106

3. Strengthening procedure

Since the Manual Lay-Up technique and the FRP Structural Repointing technique have been described elsewhere, in this paragraph some pictures about the application of CFRP rectangular bars, of stainless steel and of internal steel wires will be shown.

Figure 1 shows the epoxy being applied to fill the diagonal grooves, in which the rectangular section bars will be inserted. In figure 2 a technician is covering the mortar joints with a duck tape to help LMCP getting harder (stainless steel bars). Figure 3 refers to the internal steel net, prepared and applied during the construction f the wall itself.

Figure 1. CFRP rect bars

Figure 2. Stainless Steel bars

Figure 3. Internal steel wires

4. Test specimens

A total of ten masonry concrete blocks walls, with dimensions of 1625x1625x152.4 mm, were built with 152.4x203.2x406.4 mm concrete blocks in a running bond pattern; a total of five masonry clay bricks walls, with dimensions of 1220x1220x102 mm, were built with 51x102x203 mm clay bricks in a running bond pattern. All the walls were built by a qualified mason to not introduce additional variables, such as handwork and different mortar workability that may arise from the construction of the specimens.

The test program is shown:

- Two URM walls, W0 for concrete walls (Morbin 2001) and C01 for clay walls, were the control specimens;
- Wall WI1: strengthened with 7 internal steel circular wires, one for every horizontal mortar joint (i.e. spacing equal to 203.2 mm = 8 in);

- Wall WI2: 3 #2 GFRP circular section bars (having a diameter of 6.35 mm), one every two joints and 4 internal steel wires in the other joints, alternatively. GFRP bars were embedded into an epoxy-based paste.
- Wall WL2: GFRP laminates with the thickness of 50.8 mm at every joint (in all 7);
- Wall WL3: GFRP laminates with the thickness of 76.2 mm at every two joints (4);
- Wall WL4: CFRP laminates with a thickness of 50.8 mm at every joint (in all 7);
- Wall WT1: 3 rectangular section bars, one along the main diagonal, and two along the diagonals at 520.7 mm from the corner. They were applied in the grooves filled up with epoxy-based paste;
- Wall WT2: 5 carbon rectangular section bars, one along the main diagonal, two placed in the diagonals at 749.3 mm from the corner, and two along diagonals at 342.9 mm;
- Wall WSE: 7 stainless steel helicoidal bars embedded in an epoxy-based paste;
- Wall WSG: 7 stainless steel helicoidal bars embedded in a latex modified cementitious paste (LMCP);
- Wall WGM: 4 #2 GFRP circular bars, one in every mortar joint, using LMCP;
- Wall CB1: 7 #2 GFRP circular bars, one for second mortar joint in the front side;
- Wall CB2: the same amount of FRP bars as CB1 even in the rear side;
- Wall CL1: 76.2 mm wide CFRP laminates every 152.4 mm. Therefore, a total amount of 5 strips was applied in the front side;
- Wall CL2: reinforced in the same way as CL1, but with the same amount of laminates even in the rear side, in the same position as the front one.

For the different configurations the amount of strengthening reinforcement was equivalent in term of axial stiffness ExA (Modulus of Elasticity multiplied by Reinforcement Cross Sectional Area).

5. Test setup

The specimens were tested in a closed loop fashion. Two 30-ton-capacity hydraulic jacks, activated by a manual pump, were used to generate the load along the diagonal of the wall being tested. When loading, the force was applied to the wall by steel shoes placed at the top corner, and transmitted to similar devices at the bottom corner through high strength steel rods. Figure 4 shows the test setup. To collect displacements and the crack opening in the walls, two Linear Variable Differential Transducers (LVDTs) were placed the diagonals on each side of the walls.

Figure 4. Test Setups

6. Mechanism of failure

One-Side Strengthening

It has to be distinguished when the embedding material is the epoxy-based paste or the latex cementitious modified mortar:

- When the embedding material is the epoxy-based paste, the crack usually opens at the top-side of the horizontal reinforcement (between the paste and the masonry unit) and the failure occurs when a second crack develops, at the interface between the paste and the concrete block (see Figure 5).
- If the embedding material is the cementitious modified mortar the cracks develop over it, without changing their development and continuing its opening over the mortar (see Figure 6).

Otherwise a general mechanism of failure was observed in one-side strengthened walls: it develops in two steps: an In-Plane and an Out-of-Plane phase, as described in the following

(a) In-Plane Phase: First a crack, produced by debonding of the masonry units from the mortar, occurs in the unreinforced side and it moves through the wall thickness, until debonding of the epoxy-based paste in the joint from the masonry unit occurs; as a consequence, the wall fails because the tensile stresses are not longer transferred to the FRP. The wall cracks along the diagonal, following the mortar joints and generating a stair shape (Figure 7).

(b) Out-of-Plane Phase (Figure 8): it's due to the higher rate (Figures 9, 10) with which the cracks open in the unstrengthened side if related to the strengthened one.

Figure 5. epoxy paste embedding material

Figure 6. LMCP embedding material

Two-Sides Strengthening

In the case of two-side strengthened walls (clay walls) failure was sudden and faster than the previous-described one. It happened at higher values of load (Figures 9, 10), thanks to a no-eccentricity in the reinforcement. In fact, the presence of the reinforcement on both sides of the walls did not create the out-of-plane phase in the failure.

In these strengthened walls, the presence of the reinforcement forced the formation of diagonal cracks running through the masonry units (Figure 11) and not with the stair shape behaviour: the crack, usually, develops over the embedding material and the FRP system, without changing the path and continuing its opening over the joint. Thus, the tensile forces in the FRP bridging the diagonal crack increased the shear capacity of the walls. Beside that, as a consequence of the high loads reached, there were two cases of splitting (walls WI2 and CL2, Figure 12) and a case of sliding (wall CB2, Figure 15).

Figure 7. Star shape behaviour in one-side reinforced walls

Figure 8. Slope for the Out-of-Plane phase in one-side reinforced walls

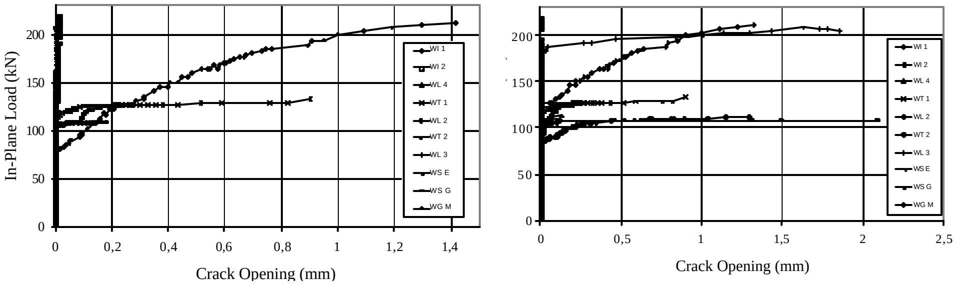

Figure 9. Crack Openings in front and rear sides of the concrete walls

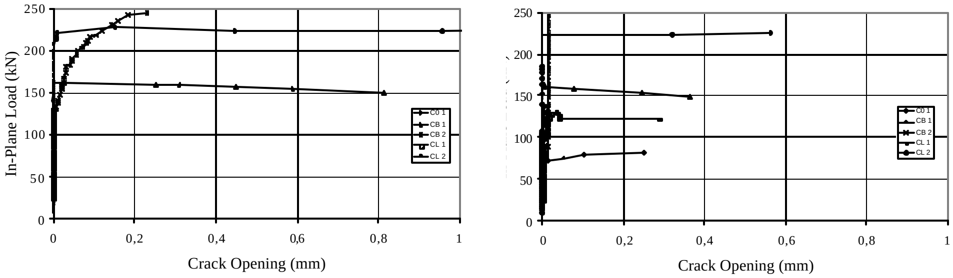

Figure 10. Crack Openings in front and rear sides of the clay walls

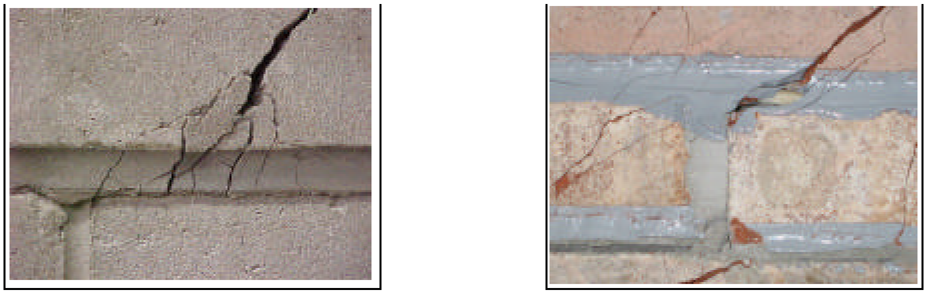

Figure 11. Crack Behaviour in one side (left) and two-sides (right) reinforcement

Figure 12. Splitting failure in wall WI 2

7. Test results analysis

Control walls, W0 and C01 showed the failure was brittle, sudden, controlled by bonding between the masonry units and mortar. All the walls failed by shear failure, but the strengthened ones had more ductility. At the final state, in all the strengthened walls a loose of material was observed only in the case of walls WI2 and CL2, due to the sliding of a mortar joint. The maximum increment in shear capacity (about 200%) was registered in three walls (WSG, CB2, CL2).

To compare the different amount and types of reinforcements, a criterion based on the shear strain was adopted. The pseudo-ductility “μ? was computed with the following relations (1) and (2):

$$m = \frac{g_u}{g_y} \tag{1}$$

$$g = |e_{90}| + |e_0| \tag{2}$$

where “g_u” is the ultimate shear strain and “g_y” is the yielding shear strain. Considering the strains generated by the diagonals load as principal strains, the maximum shear strain is expressed as the sum of them (“e_0” and “e_{90}”); this allows to comprise both sides and all the cracks movements, like an average (Grando, 2002). Results are given in Table 2

Table 2. Comparison of Pseudo-ductility

Specimen	**Load*u***		**Load*y***		g_y	g_u	m
	kN	kips	kN	kips			
W 0	108.09	24.3	-	-	0.09	0.09	1.00
WI 1	211.73	47.6	-	-	0.0505	1.075	22.28
WI 2	160.14	36.0	-	-	0.037	0.11	2.97
WL 2	111.20	25.0	-	-	0.036	0.34	9.44
WL 3	208.18	46.8	-	-	0.0311	0.611	19.67
WL 4	112.98	25.4	-	-	0.145	1.294	8.8
WT 1	133.45	30.0	-	-	0.0558	0.952	17.06
WT 2	108.54	24.4	-	-	0.116	1.082	9.32
WS E	126.33	28.4	-	-	0.0845	0.213	2.5
WS G	219.74	49.4	-	-	-	-	-
WG M	184.16	41.4	-	-	0.0063	0.1322	20.9
C0 1	82.73	18.6	82.73	18.6	0.1603	0.1603	1
CB 1	149.46	33.6	163.69	36.8	0.1253	0.7129	5.69
CB 2	245.53	55.2	245.53	55.2	0.0501	0.296	5.91
CL 1	121.87	27.4	129.88	29.2	0.014	0.106	7.78
CL 2	225.07	50.6	225.07	50.6	0.057	0.944	16.56

Figure 13 shows the In-Plane Load vs. Shear Strain curves for all the tested walls. It is possible to observe that the best behaviour is detected for the wall CL2, reinforced with a symmetric distribution of laminates on both sides. This increased both the ultimate capacity and the Pseudo-Ductility. In particular, this wall failed with a sliding of the fifth joint, after a first shear failure.

The good behaviour of the clay panels, in comparison with the similar concrete walls, is due to the fact that the mortar can get inside the holes of the bricks and create a solid system (see Figure 14). This becomes like a dowel-action effect of the mortar and increases the capacity of the wall itself. The splitting failure (Figure 11), obtained in the central zone along the compressed diagonal in wall CB2, was due to a great tangential strain, resulting from the high bond between the clay bricks and from the symmetric reinforcement (#2 GFRP bars both sides). The splitting failure (Figure 12), obtained in the upper corner along the compressed diagonal in wall WI2 is probably due to an incorrect test setup. The sliding failure (Figure 15) obtained in wall CL2 was due to the combination between the increase of the ultimate load (thanks to the presence of the reinforcement over both sides) and the lower strength in an unreinforced joint of mortar. However, in this case, a larger increase in shear capacity was recorded, thanks to the fact that the horizontal laminates engaged the masonry layers where the sliding occurred, and the cracks running along the head joints were bridged.

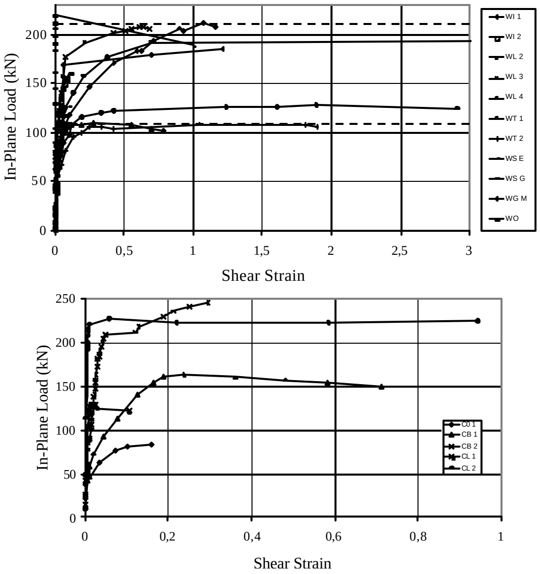

Figure 13. In-Plane vs. Shear Strain curves for concrete and clay walls

Figure 14. Dowel action effect

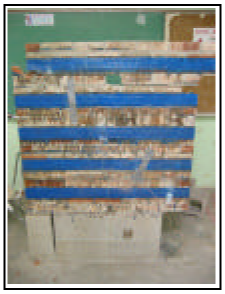

Figure 15. Sliding Failure

8. Conclusions

From this experimental research the following conclusions can be drawn:

(a) Remarkable increases in shear capacity and pseudo-ductility, up to 200%, can be achieved. These increments can be reached mainly if the reinforce has a symmetric shape.

(b) The combination "stainless steel (Helifix™) – epoxy paste" is not effective for strengthening because the stiffness of the steel rods is too high, and the bond between the epoxy and the concrete does not allow sliding along the crack.

(c) The system "stainless steel (Helifix™) – mortar (Sonopatch 100™)" allows sliding along the crack, even on the strengthened surface, increasing the capacity of the wall.

(d) There is a considerable dependence of this type of test from the preparation of the specimens, in particular way from the amount and type of mortar.

(e) In the one-side reinforced walls two failure phases were identified: In-Plane and Out-of-Plane. The In-Plane component was the most critical and related with the stair-development of the crack, the Out-of-Plane could be observed with the slope of the wall. These walls showed a not so high increase in terms of pseudo-ductility.

(f) In the two-side reinforced walls, the symmetric reinforcement had the consequence of an increase in the first crack load, the ultimate load and the pseudo-ductility.

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