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STRUCTURAL POLYMER GRID REINFORCEMENT FOR BRICK MASONRY WALLS – THE DUCTILE APPROACH

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Abstract

Reinforcing brick masonry walls with a structural polymer grid embedded in the plaster can be an effective alternative to change its traditionally brittle seismic behaviour into an energy dissipation system that would allow masonry buildings to successfully stand earthquake forces.

This report describes the work performed to investigate the post elastic effect of reinforcing masonry brick walls with a structural polymer grid applied on its surface and embedded in a sand cement plaster. Twelve 1.20 x 1.20m panels were built and tested to cyclic shear force with constant vertical compression load; another twelve 0.80 x 1.60 brick panels were built and subjected to transverse flexural monotonic loading and unloading test. Solid clay bricks were used for the construction of walls with different type of mortar for the layers and for the plaster, in an attempt to better simulate retrofitting conditions. For the shear-compression tests, four walls were tested without plaster, four with sand cement plaster and the last four with the grid reinforcement embedded in the plaster on both sides. For the flexural tests, the variables studied were the effect of plaster alone, the effect of the polymer grid applied on the tension and compression side and the effect of the vertical load. The results of the shear-compression tests indicated a small increment in the in-plane wall shear resistance due to the grid presence, and that there is almost no evidence of any increment in stiffness, the grid deformability, being much higher than that of the plaster, practically does not contribute significantly to the masonry strength, they showed however, a substantial increase of energy dissipation with respect to the unreinforced panels. Important results have been obtained from the out-of-plane load tests. They have clearly demonstrated the positive effects of the grid presence on the ultimate load, ultimate displacement and energy dissipation. These results have allowed developing an initial mathematical expression for the ultimate moment capacity of masonry walls reinforced with polymer grids.

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Introduction

Polymer grids used as reinforcement for masonry walls appears in these days as an alternative for retrofitting non reinforced masonry walls in seismic areas around the world. An additional advantage of this grid is that can be used in historical constructions since ancient plasters include lime and gypsum in the mortar and the polymer grid is not affected by its chemical components. The post elastic behaviour of reinforced walls subjected to in plane cyclic shear forces and out of plane bending is a key issue to investigate the change from a traditionally brittle seismic behaviour into an energy dissipation system that would allow masonry buildings to successfully stand earthquake forces.

Specimens Description

Twelve square panels 1.2 x 1.2m (Figure 1) were tested to in plane cyclic shear force and twelve panels 0.80 x 1.60m (Figure 2) were tested to monotonic out of plane bending. Wall thickness in both cases was 220mm for the non plastered walls and 260mm when plastered on both sides. Solid bricks 110x 220x70mm from the current industrial production were used to built the panels, laying the bricks with a mortar of 1:1:7 (cement: lime: sand): The mortar for the plaster was 1:1:5, stronger than the mortar used for laying the bricks, in an attempt to simulate real retrofitting conditions.

Concrete beams 220 x 200mm at the bottom and top were built to transmit the vertical and horizontal loads in the square panels and to transmit vertical load and to work as horizontal support in the case of the panels subjected to bending.

Table 1 shows the identification of plain panels, non reinforced plastered panels and the reinforced panels. Four of each type was tested to cyclic shear force and constant compression load.

As seen in Table 2, the flexural panels, can be divided in two main categories: the non reinforced panels, and the reinforced panels; the non reinforced panels had two sub-categories, with and without plaster; and the reinforced panels had three sub- categories, with vertical load, without vertical load and with the reinforcement overlapped at mid span. A single panel with reinforcement on the compression side was also tested. The panels were subjected to different maximum horizontal displacements based on the judgement about its observed stability.

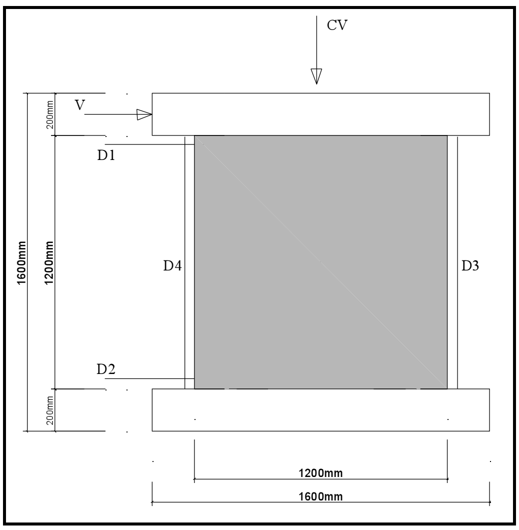

Figure 1. Shear-Compression panels.

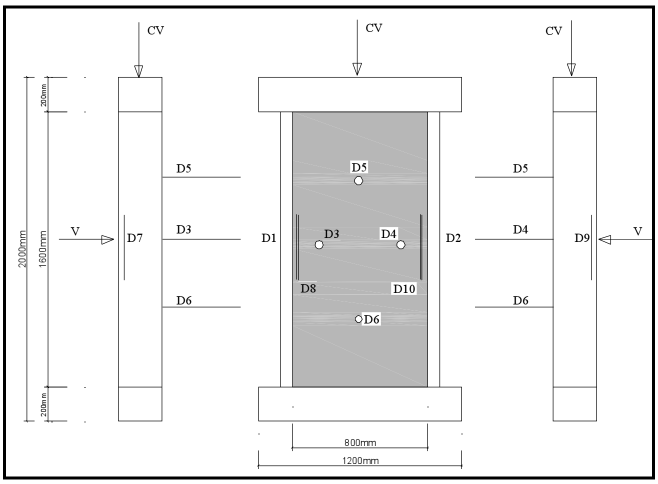

Figure 2. Flexural panels.

Table1. Identification of the shear-compression panels

Panel Id.	Plaster	Polymer grid	Vertical stress (Mpa)
SC-1 to SC-4	No	No	0,75
SC-5 to SC-8	Both faces	No	0,75
SC-9 to SC-12	Both faces	Both faces	0,75

Table2. Identification of the flexural panels

Panel Id.	Plaster	Grid reinforcement	Vertical stress (MPa)
F-1 and F-2	Both sides	No	0,50
F-3 and F-4	No	No	0,50
F-5, F-6, F-9	Both sides	On the tension side	0,50
F-7 and F-8	Both sides	On the tension side	-------
F-10	Both sides	On the compression side	0,50
F-11 and F-12	Both sides	Tension side overlapping	0,50

Material properties

Masonry properties were obtained from simple component tests. Brick samples were subjected to dimensional variation, absorption, density and axial compression tests, the average density was 1.83gr/cm3 and the average compressive strength of full bricks was 5.49Mpa. The mortar for the layers was a mix of cement, lime and coarse sand 1:1:7 in volume proportion. This mortar had an average strength of 4.21Mpa. The mortar for the plaster was a mix of cement, lime and coarse sand with a volume proportion of 1:1:5. This mortar had an average compressive strength of 7.12Mpa.
Compressive strength of masonry was measured in piles of five brick units; joint thickness and mortar quality were similar to testing panel. A total of five piles were tested and the average compressive strength obtained was 3.68Mpa.
Five wallets of dimensions 440 x 440 x 220mm were subjected to diagonal tension test (ASTM 1981) in order to obtain the ultimate shear strength of masonry. Typical failure cut the mortar and the brick units what means a good bonding between mortar and bricks. Average compressive strength obtained was 0.35Mpa.
The tension resistance of the grid was estimated from tensile tests in two orthogonal directions obtaining 47kN/m in the longitudinal and 34kN/m in the transversal direction

Construction procedure

Every panel was built on a 220 x 200mm reinforced concrete beam; the bricks were cleaned with a brush and submerged in water for approximately 1.5 minutes before lying. The amount of water in the mortar was such as to allow an adequate workability during the construction of the wall. Horizontal and vertical joints were 15mm for all panels. A top reinforced concrete beam 220 x 200mm was placed to transmit vertical and horizontal loads to the panels. The polymer grid used as reinforcement was anchored to the panels using 50mm steel anchors in pre drilled holes spaced 400mm horizontal and vertically (Figure 3). In two of the bending panels, the grid was placed with 150mm overlapping at the mid span with no anchors placed in the overlapping area. Each wall of the panel was watering before applying the 2cm mortar plaster (Figure 4).

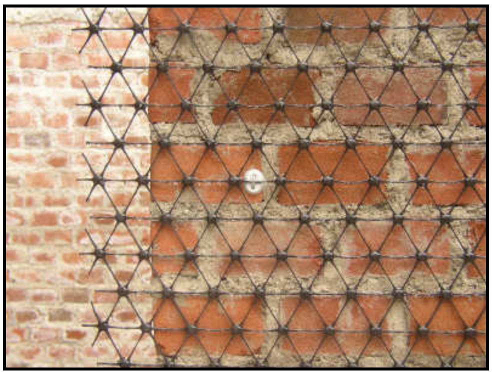

Figure 4. Polymer grid on panel.

Figure 5. Plastering the panel.

Testing procedure and Instrumentation

Shear – compression tests

The horizontal force was applied at the top beam with a 500kN MTS hydraulic actuator. The vertical load was applied with one manual pump in the case of the non reinforced panels (Figure 6) and with two symmetrical pumps for the reinforced panels (Figure 7). Six displacement transducers D1 to D6 were used in this test: D1 was used to control the actuator, D2 to monitor the sliding at the base, D3 and D4 for the vertical displacement at both ends and, D5 and D6 to monitor diagonal cracks in the panel (Figure 1).

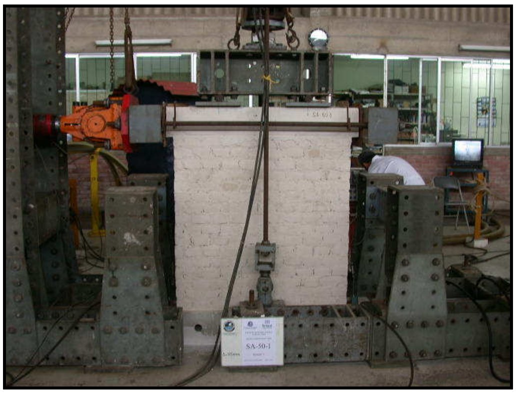

Figure 6. Set up for non reinforced panels

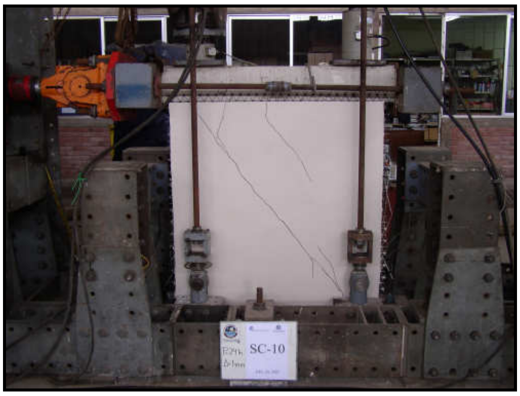

Figure 7 Set up and for reinforced panels.

Flexural tests.

Upper and lower beams were used to connect the horizontal reactions to the load applied at mid span, upper beam was also used to apply vertical constant load (Figure 8). Ten displacement transducers were used in this test. D1 and D2 measure the total vertical displacement, D3 to D6 the out of plane displacement; D7 and D8 the vertical displacement at mid span in the tension side; and finally D9 and D10 measure the vertical displacement at mid span in the compression side.

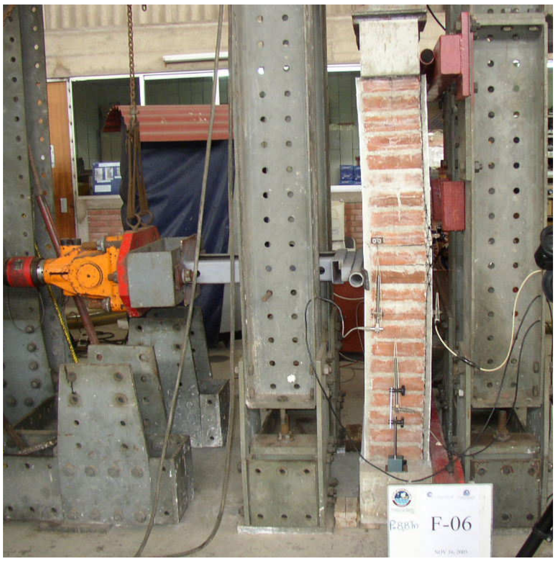

Figure 8. Experimental set up for flexural panels.

The vertical load had a constant value of 88kN in all panels with the exception of panels F7 and F8 that were tested without vertical load. The test was conducted under displacement control using D3 and D4 as control displacements.

Experimental results

Description and visual observations made during testing and interpretation of instrumental data are presented in this section.

Shear-compression tests

In all panels tested on shear–compression forces horizontal cracks appeared at the base of panel on both sides, produced by the effect of in plane bending moment that the vertical load applied is not able to counteract. Therefore, in addition to the deformation of the panel, the upper horizontal transducer recorded also the rigid body rotation of panels. Nevertheless, in all panels except one, the goal of obtaining a failure mode with diagonal shear cracks was attained. The final observed behaviour was very different in the three types of panels, even though all panels started with a horizontal tension crack at the base.
For plain masonry panels, (Figure 9) at +/- 2mm maximum displacement and 70kN of horizontal load, tension cracks appeared at both sides of panel base. When reaching 4mm of horizontal displacement, with a horizontal load of 90kN, vertical compression cracks appeared at both ends of the panel; the above mentioned tension cracks extended and enlarged, leading to the appearance of the first small diagonal cracks. The diagonal and tension cracks enlarged at +/-7mm of horizontal displacement until complete diagonal cracks appeared at +/-10mm horizontal displacement and the force-displacement curve began to decrease (Figure 10). The maximum average load reached was 98kN.

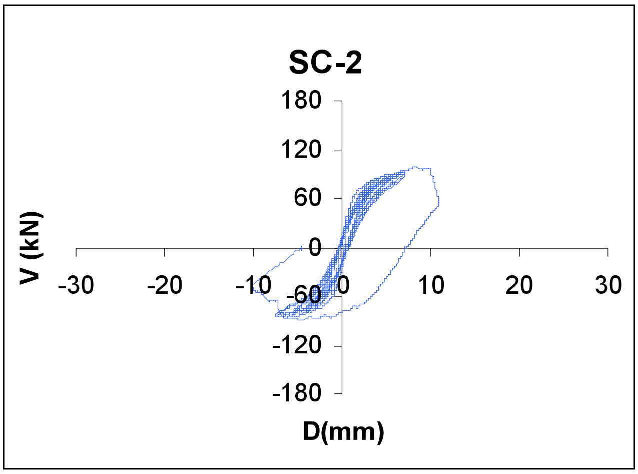

Figure 9. SC-2 - Force - displacement curve

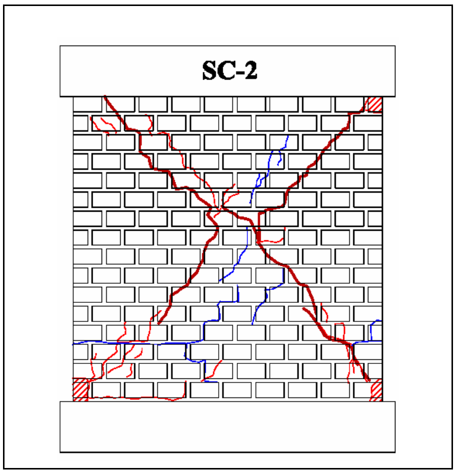

Figure 10. Crack pattern SC-2

For plastered panels (Figure 11), (SC-5 to SC-8), at +/-2mm horizontal displacement and 100kN horizontal load, tension cracks appeared at both sides of panel base. Vertical compression cracks appeared at +/-10mm, at +/- 15mm a sudden failure took place with a wide open diagonal crack detaching the plaster in the compression toe meaning the end of the test (Figure 12). The maximum average horizontal load was 120kN.

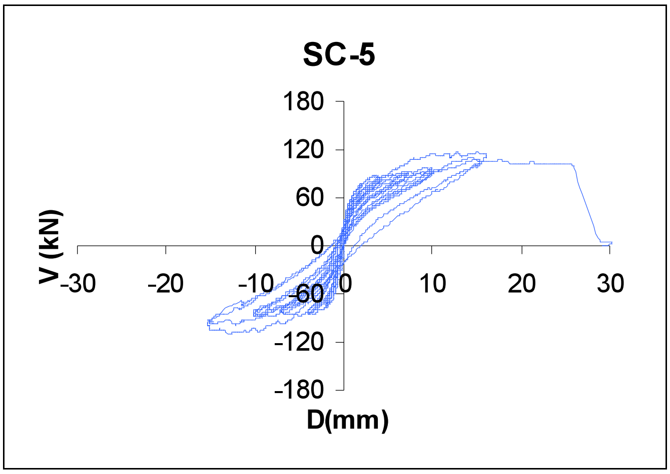

Figure 11. SC-5 - Force-Displacement curve.

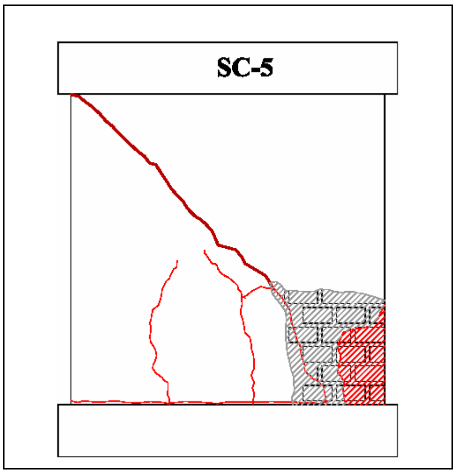

Figure 12. Crack pattern SC-5.

In the first panel reinforced with the polymer grid (SC-9), the experimental setup used in the previous panels with the vertical load in a single position at the mid span, was not able to produce the diagonal crack. For panels SC-10 to SC-12, the test setup was modified to apply the vertical load in two points near the end of panel in an attempt to better control the rotation of the specimen. Figure 13 shows the F-D curve obtained for the reinforced panels, with more dissipated energy than the non reinforced panels.

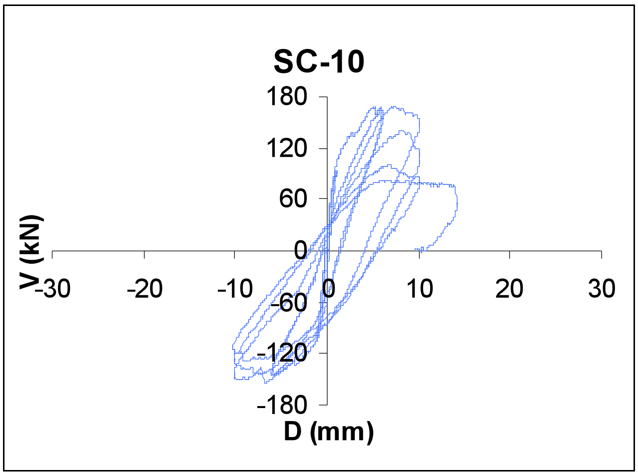

Figure 13. SC-10 - Force-Displacement curve.

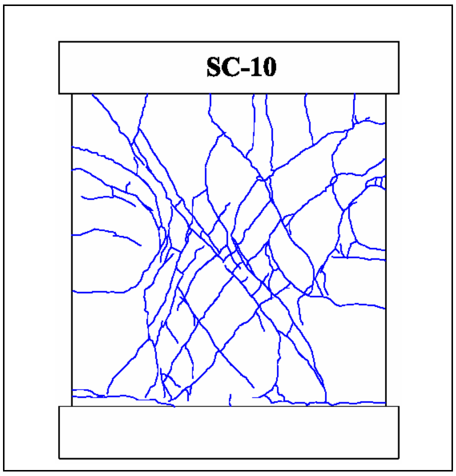

Figure 14. Crack pattern SC-10.

The observed behavior of panels tested in flexure, can be divided in two main categories: the non reinforced panels, and the reinforced panels; the non reinforced panels had two sub-categories, with and without plaster and the reinforced panels had three sub-categories, with vertical load, without vertical load and with the reinforcement overlapped at mid span. A single panel with reinforcement on the compression side was also tested. The panels were subjected to different maximum horizontal displacements based on the judgement about its observed stability.

In Figure 14, the crack pattern after SC testing shows that he grid reinforcement distribute the damage in several fine cracks in both diagonal directions, compared to the plastered, non reinforced panels where one wide crack appears. The plaster increases the horizontal resistance. Investigation of the grid state after the test shows neither damage on the grid or inelastic deformation which implies that the tensile stress of the grid during the tests has been in the elastic range.

Quantification of absorbed energy (dashed area) and dissipated energy (cross dashed area) for panels 2, 5 and 10 are shown on plots in Figure 15 and the values of computed energy in Table 3. The absorbed energy was computing using the envelope curve of force-displacement curves including also the rotation of the panel with respect to the base; this is why the non reinforced and plastered panel (SC-5) reaches a higher value than the plain panel (SC-2). The dissipated energy was computed using the last stable cycle of each test. Table 3 shows that the use of grid reinforcement increases the dissipated energy more than twice with respect to the non reinforced panel and four times with respect to the plain panel.

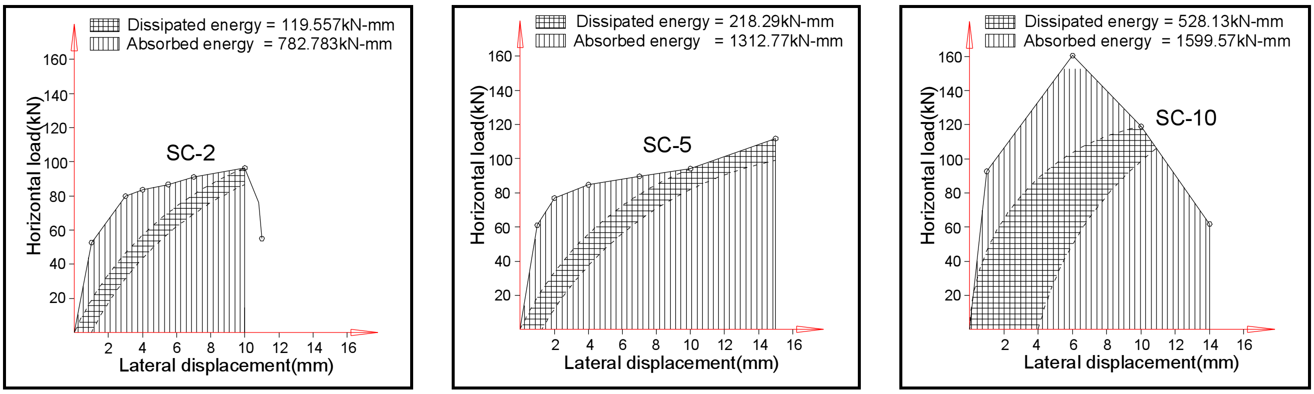

Figure 15 Computation of absorbed and dissipated energy for three types of panels.

Table 3 Absorbed and dissipated energy for three types of panels

Panel ID	Absorbed Energy kN-mm	Dissipated Energy kN-mm
SC-2	782	119
SC-5	1312	218
SC-10	1599	528

Flexural tests

For the non reinforced panels, the failure mode consisted in a single horizontal crack near mid span that opens progressively until it crosses almost all the panel width (Figure 17). Plain panels reached a maximum horizontal load of 40kN and plastered panels 60kN (Figure 16).

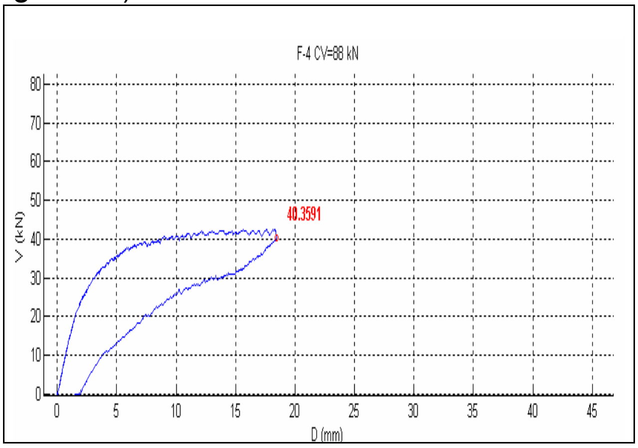

Figure 16. F-4 Force-Displacement curve

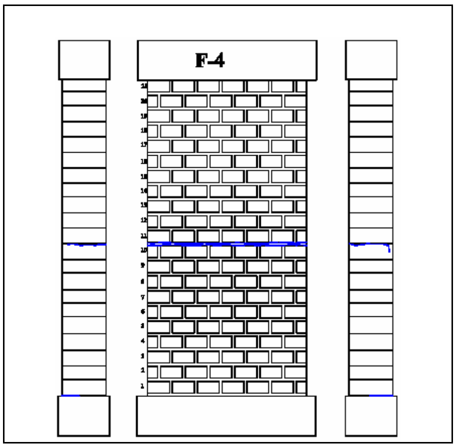

Figure 17. Crack pattern F-4

For panels with reinforcement on the tension side and vertical load, the crack pattern was scatter with several horizontal cracks near mid span; the average maximum horizontal load was 70kn and for the maximum displacement, two panels had 23mm in average and panel F-9 reached 43mm (Figure 18). For panels without vertical load, the crack pattern was even more scattering with many more horizontal cracks near mid span; in this case the maximum load was slightly higher than 20kN and an average of 43mm for the horizontal displacement.

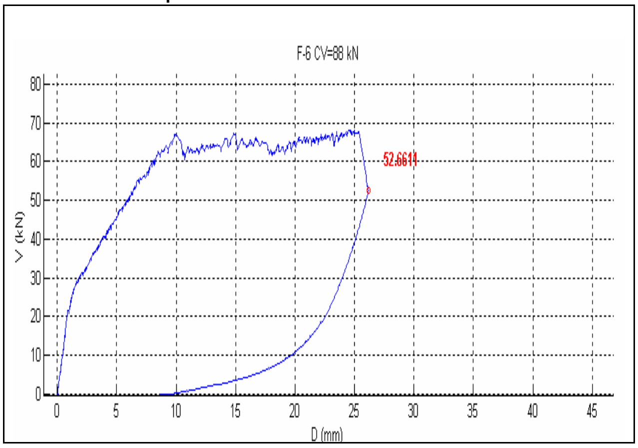

Figure 18. F-6 Force-Displacement curve

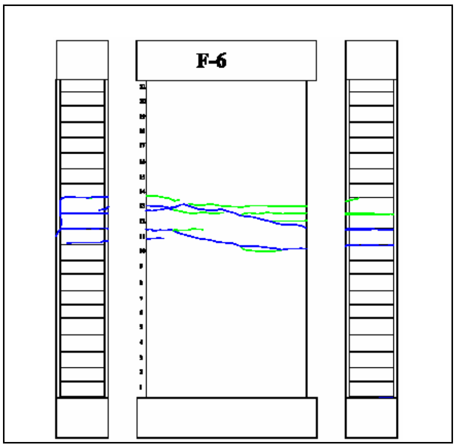

Figure 19. Crack pattern F-6.

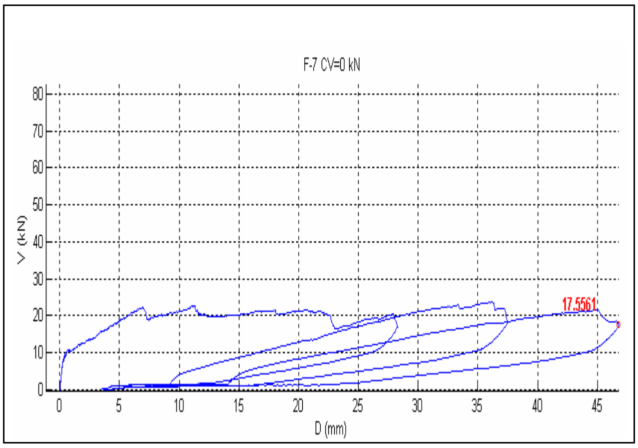

Figure 20. F-7 Force-Displacement curve

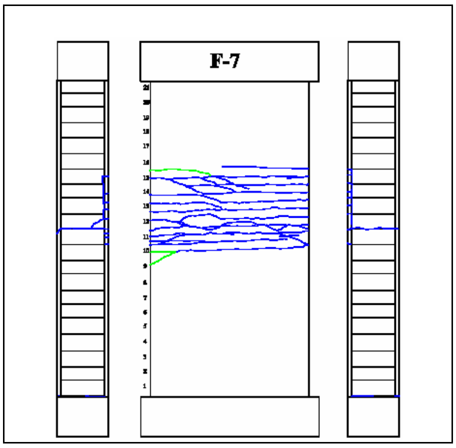

Figure 21. Crack pattern F-7.

Figures 22 and 23 show the behaviour of panels with 15cm overlapped reinforcement at mid span behaved in the same way than the previous reinforced panels, but the cracks were situated outside the overlapped area, reaching a maximum load near 80kN and being the maximum displacement 34mm and 45mm.

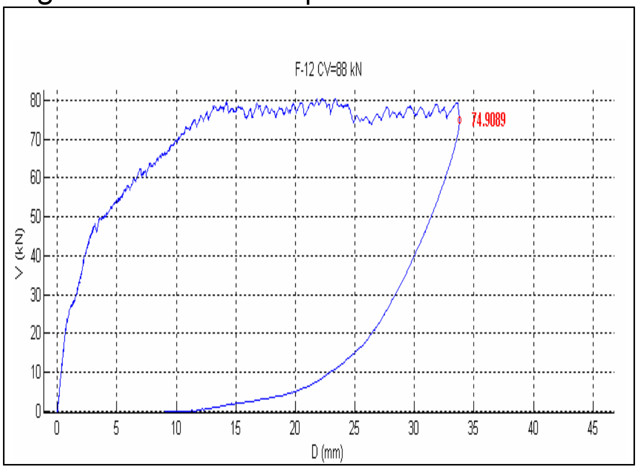

Figure 22. F-12 Force-Displacement curve

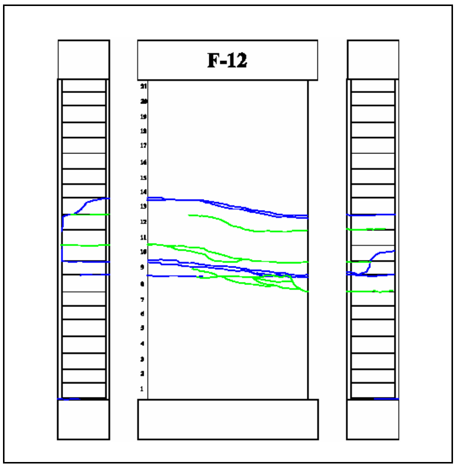

Figure 23. Crack pattern F-12.

The only panel with the reinforcement in the compression side produced a single crack that opened progressively crossing the width of the panel but stopping at the grid position preserving the compression zone free of cracks and allowing a more stable behaviour. The maximum horizontal load was 60kN for 10mm horizontal displacement, kept constant until 40mm of displacement.

Analytical interpretation of flexural experimental results

An adaptation of the Analysis for Unreinforced Walls Subjected to Out-Of-Plane Excitation (Priestley 1992) has been used to develop an empirical expression for the ultimate bending resistance of walls reinforced with polymer grid. The analysis is based on the experimental results and superimposing the effects of the plain panel with vertical load and the reinforced panel without vertical load.

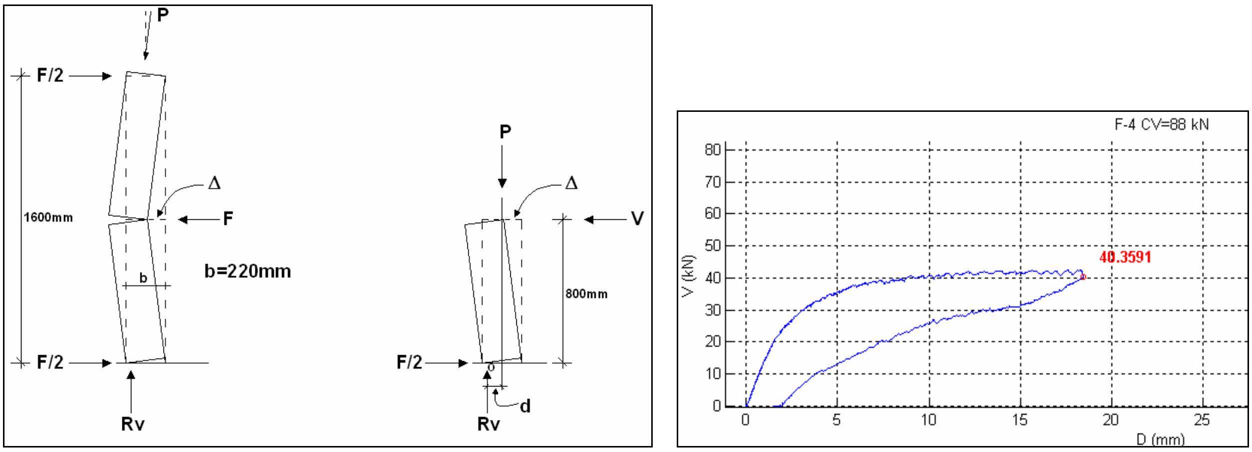

Figure 24. Out-of-plane response of plain walls with vertical load and F-D curve for F-4.

Figure 24 shows the forces acting on the panel F-4 at ultimate stage, were D is the central lateral displacement, F is the lateral force and P is the vertical load acting on the panel. The panel own weight is not taken in account since it has little influence with respect to the applied vertical load. Moment equilibrium of the lower portion of the wall about point o gives the following equation:

$$Pd = \left(\frac{F}{2}\right)800 \qquad \textbf{[1]}$$

From the plot F-D for panel F-4 shown in the same figure, a value of 40kN is obtained for F, this value is approximately constant for the horizontal part of the plot. The value for P is 88kN, also constant during the test. Therefore, a value of d = 181mm is obtained from equation 1. By other hand, the value of *d* as function of the displacement Δ is as follows

$$d = e - \Delta d \qquad \textbf{[2]}$$

Were e is the distance between the load *P* and the vertical reaction at the base *Rv.* At ultimate state, Δ = 18mm; therefore e = 199mm.

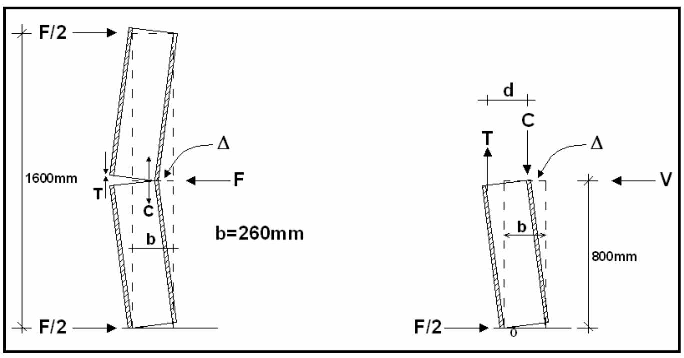

Figure 25. Out-of-plane response of panels reinforced with polymer grid, without vertical load.

Figure 25 shows the forces acting on panel F-7 at ultimate stage. In this case d is the distance between the compression and tension forces, it has a constant value independent from Δ and can be estimated from the observation of F-7 flexural test as 240mm at ultimate stage. From the simple equilibrium equation:

$$T(240) = \left(\frac{F}{2}\right)800 \qquad \textbf{[3]}$$

Were the value for F (from figure 20) is 20kN, approximately constant for Δ from 7 to 45mm, this equation yields an ultimate bending moment of 8,000kN-mm and the tension force in the grid (T) a value of 33kN.

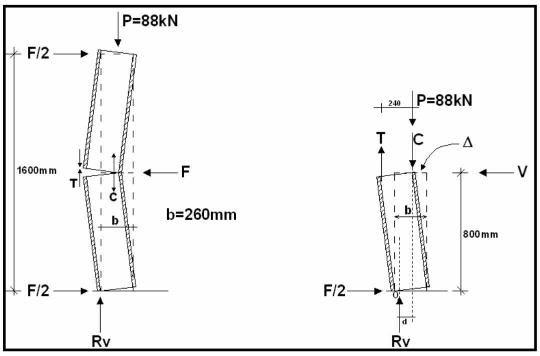

Figure 26. Out-of-plane response of reinforced panels with additional vertical load.

In order to analyze the forces acting on the reinforced panel with additional vertical load shown in Figure 26, the equilibrium equation is expressed as the sum of effects taking separately, the influence of vertical load and the influence of reinforcement:

$$88d + 240T = \left(\frac{F}{2}\right)800 \quad \textbf{[4]}$$

Were 240T has a value of 8,000kN-mm and $d = (e - \Delta)$. Replacing the values of 65kN for F and 25mm for Δ, from F-6 F-D curve (Figure 18), the values of 204mm for *d* and 229mm for *e* are obtained. In all cases, the values of *e* are approximately 90% of the panel thickness, therefore a final expression for the ultimate bending moment can be stated as:

$$Mu = 0.9b\,(P + 0.9F_g) \quad \textbf{[5]}$$

Were b is the panel thickness, P the vertical load and F_g the ultimate tension force in the grid. In each case, it has been verified that the value for the compression force is near but do not exceed the ultimate compressive strength of the mortar.

Conclusions

For the shear-compression panels, an important consideration concerns the status of failure shown by reinforced panels with respect to the bare and unreinforced ones. Bare and unreinforced panels show very neat cracks approximately along one or two diagonals of the panels, whereas reinforced panels are characterised by a grid of cracks suggesting that the panel collapse requires the formation of a large number of failure surfaces, with a higher value of ultimate strength and dissipation of energy.

The previous conclusion is confirmed by the computation of absorbed and dissipated energy from F-D curves for one panel of each type, showing clear advantage of the reinforced panel with respect to the unreinforced ones.

The flexural tests have clearly demonstrated the positive effects of the grid reinforcement on all significant mechanical parameters of the panel, being these the ultimate load, ultimate displacement and energy dissipation.

The widely spread distribution of cracks specially on the flexural panels without vertical load, put into evidence the beneficial contribution of the grid related to the mitigation of the damage peak and to the increase in energy dissipation due to the spreading of the damage.

The brittle effect that the plaster seems to have on bare panels is eliminated by the grid that enhances the ductile behaviour of the panel.

Tests with overlapped grid for a length of 150mm have shown the adequacy of the overlapping length and also an increment of bending resistance suggesting that a double layer of reinforcement can be beneficial.

An initial empirical formula for estimating the ultimate resistant moment of walls reinforced with polymer grids has been derived from the analytical interpretation of the flexural results using ordinary methods of the theory of structures. Therefore additional tests results can be used to support analytical methods usable in ordinary design procedures.

Acknowledgments

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