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# EXPERIMENTAL RESPONSE OF MASONRY WALLS EXTERNALLY REINFORCED WITH CARBON FIBER FABRICS

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## ABSTRACT

Recent earthquakes have produced extensive damage in a large number of existing unreinforced masonry (URM) buildings, showing the need for retrofit techniques for masonry structures. Six URM shear-walls externally reinforced with bonded carbon fiber reinforced polymer (CFRP) sheets were tested under in-plane shear load. Walls with two configurations of the reinforcement were subjected to cyclic loading. Externally bonded CFRP reinforcement sharply increases the shear strength of URM walls and their deformation capacity, spreading the cracks in to several thinner cracks. The failure mode was less destructive than URM in walls. A model that produces good estimates of the strength of the reinforced walls was proposed. As future work 18 full scale masonry walls, with various configurations of exterior fabric reinforcement, including single side reinforcement, will be tested, and a design methodology will be proposed.

## Introduction

The 1985 earthquake in Chile produced extensive damage in reinforced masonry buildings with more than 3 stories due to in-plane shear actions (Cruz et al. 1988). In recent earthquakes unreinforced masonry structures, used in historical buildings as well as in current modern construction, have sustained a high degree of damage due to shear action, demonstrating the need for techniques to improve the seismic response of those structures.

A retrofit technique for masonry structures that has been under study in recent years is the use of externally bonded FRP (Fiber Reinforced Polymers) laminates or fabric sheets. FRP is a material made of high strength fibers (glass, aramid, carbon) embedded in a polymeric resin matrix. The fibers resist tension while the resin transfers the loads among the fibers. The most

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common use of FRP is as external reinforcement for reinforced concrete elements. Externally bonded FRP fabric has as advantages low weight-strength ratio, short installation periods, and very low intervention on the structure.

Previous researchers (Ehsani et al., 1999, Hamoush et al., 2001, Albert et al., 2001) have shown that carbon and glass fibers used as laminates or fabric sheets are effective in increasing the out-of-plane strength and ductility of reinforced and unreinforced masonry walls. Little investigation on the use of externally bonded FRP laminates or fabric as in-plane shear reinforcement of masonry walls has been reported. Some experimental results (Schwegler, 1995, Priestley and Sieble, 1995 and Laursen et al., 1995) have shown that masonry walls externally reinforced with FRP and subjected to in-plane shear have large increase of strength and load deformation capacity. Others (Valluzi et al., 2002 and Santa Maria et al., 2004) reported that masonry panels externally reinforced with FRP and subjected to diagonal compression have between 15 and 70% increase of strength. In terms of shear strength a diagonal configuration was more efficient than a grid configuration. No difference in the response between monotonic and cyclic loading was found (Santa Maria et al., 2004).

Two URM walls and four URM walls with externally bonded CFRP were subjected to in-plane cyclic loading. Two external reinforcement configurations were used: diagonal and horizontal. The objective of these tests was to quantify the improvement in shear resistance and to study the effect of the orientation of the reinforcement in the behavior of the walls.

## Experimental Program

As part of an ongoing investigation that includes the shear test of 24 full scale masonry walls made of hollow clay bricks six walls with external FRP reinforcement were tested under in-plane shear load. The variables considered in this investigation are the ratio of FRP reinforcement and its configuration.

### Materials

The FRP reinforcement consisted of a woven carbon fabric, laminated and bonded on site. The dimensions and main mechanical characteristics of the fabric, according to the fabricator, are shown in Table 1.

Table 1. Nominal dimensions and mechanical properties of the FRP reinforcement

| | |
|---|---|
| Nominal thickness, $t_f$ (mm) | 0.13 |
| Characteristic tensile strength (N/mm$^2$) | 3500 |
| Tensile modulus of elasticity (N/mm$^2$) | 23000 0 |
| Ultimate tensile strain (%) | 1.5 |

The masonry bricks were machine made hollow clay bricks (140x290x112 mm). The average prismatic strength was 11.0 MPa. The average shear strength measured in diagonal compression tests of 650x650 mm wallets was 0.85 MPa. Commercially available premixed mortar was used, with average compressive 25.0 MPa. The concrete of the top and bottom beams had compressive strengths at 28 days that varied between 13 MPa and 35 MPa.

**Test specimens**

The six masonry walls consisted of a bottom and a top reinforced concrete transfer beams (400x330 mm and 400x300 mm, respectively) to anchorage the walls to the reaction frame; a bottom and top beam (150x200 mm); and the masonry wall with nominal dimensions of 1975x2000x140 mm. Two 25 mm steel bars were placed at the corners of the walls to avoid flexural failure before shear failure occurs. Two horizontally reinforced walls (HRM) had three horizontal strips of carbon fabric bonded on each side, and two diagonally reinforced walls (DRM) had one strip bonded to each diagonal, on each side of the walls. Two walls were not reinforced.

To prepare the surface of the walls the exterior layer of the bricks was removed with a sander until the clay substrate was exposed. The gaps between bricks were filled with a mortar reinforced with fibers to produce a smoother surface. The surface obtained was not planar, but it had rounded irregularities. The fabric was bonded to the surface of the walls using an epoxy resin as recommended by the fabricator. The process of surface preparation and bonding of the carbon fibers is shown in Fig. 1. The configurations of the reinforcement are shown in Fig. 2.

(a) (b)

Figure 1. (a) Surface treatment of the walls. (b) Bonding of the FRP reinforcement.

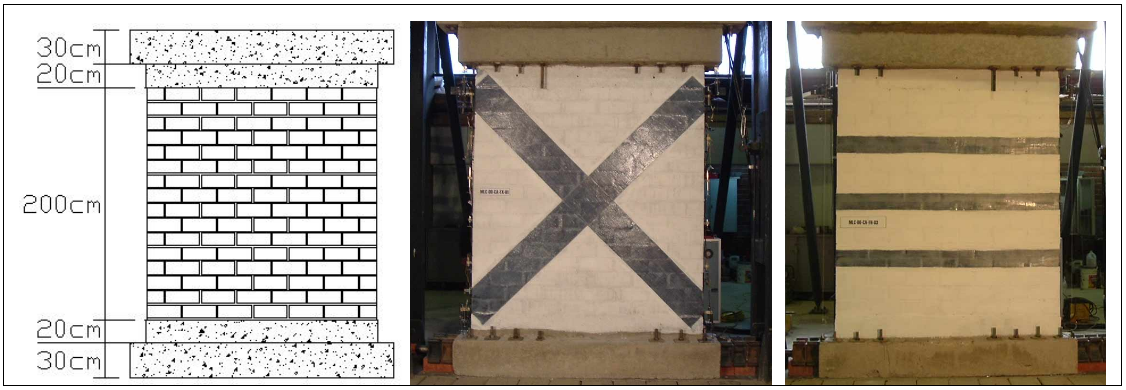



Figure 2. Configurations of the exterior reinforcement.

The configuration of the reinforcement, the total amount of fabric used in each wall and the reinforcement ratio are shown in Table 2. The reinforcement ratio $\rho$ was calculated as follows:

$$\rho = (b_f * t_f) * \cos\alpha / (h * b) \quad (1)$$

where $b_f$ and $t_f$ are the total width and thickness of the fabric that is crossing the diagonal cracks, $\alpha$ is the angle between the fibers of the fabric and the lines of bricks, and h and b are the height and the thickness of the masonry wall.

Table 2. FRP Reinforcement of the walls tested.

| **Specimen name** | **Reinforcement configuration** | **Strip width $b_f$ (mm)** | **Total area of reinforcement ($m^2$)** | **Ratio of FRP reinforcement (%)** |
|---|---|---|---|---|
| MLC-00-CA-SF-01 | - | - | - | - |
| MLC-00-CA-SF-02 | - | - | - | - |
| MLC-00-CA-FX-01 | Diagonal | 300 | 3.37 | 0.20 |
| MLC-00-CA-FX-03 | Diagonal | 200 | 2.25 | 0.13 |
| MLC-00-CA-FH-02 | Horizontal | 150 | 1.78 | 0.42 |
| MLC-00-CA-FH-04 | Horizontal | 100 | 1.19 | 0.28 |

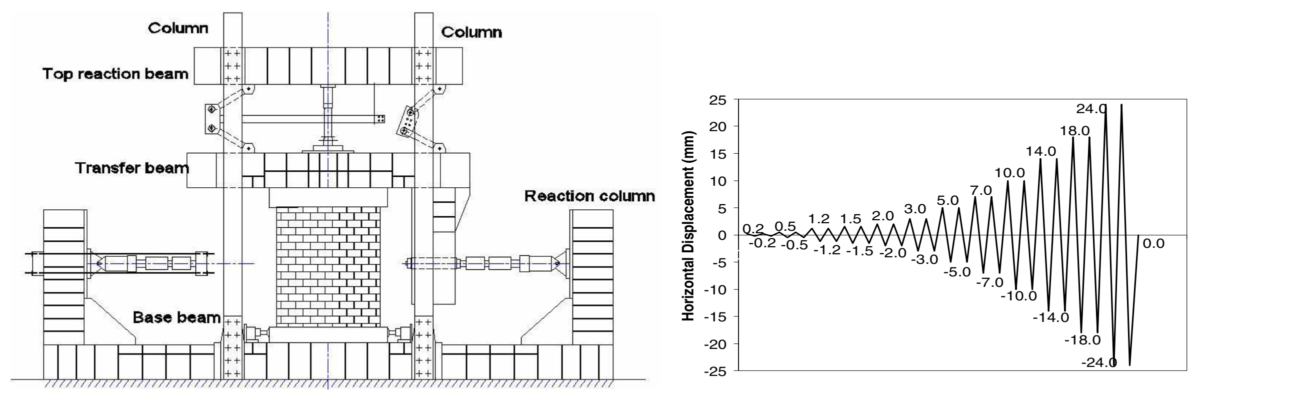
### Test Procedure

The walls were subjected to displacement controlled in-plane cyclic shear load, and a simultaneous constant vertical load, by means of hydraulic rams attached to the reaction frame shown in Fig. 4. The horizontal loading consisted of two cycles at each displacement level, starting at 0.2 mm and up to 24 mm if failure did not occur before. See Fig. 4 for the lateral displacement program applied to the walls. The nominal vertical load was 98 kN, corresponding approximately to the first floor load of a three story building with concrete slabs in two floors and a light roof. The walls were fixed to the floor and free to rotate at the top. The load was applied 1700 mm from the top of the bottom transfer beam, giving an aspect ratio M/Vd of 0.86.

The horizontal displacement was measured at the top transfer beam. Also was measured relative rotation between the top and bottom of the walls.

## Discussion of Test Results

In Table 3 are shown the average vertical load; the maximum thickness of the first major crack, defined as the first crack that covers at least 70% of the lines of bricks of the walls, the horizontal displacement and load at which the crack occurs; and the average of the maximum horizontal load with its corresponding displacement. Also are reported the average maximum load of the URM walls, the ratio of reinforced to unreinforced wall strengths, and the ratio of the increase in strength to the amount of reinforcement used.




(a) (b)

Figure 4. (a) Reaction frame. (b) Horizontal displacement program for the cyclic shear tests.

Table 3. Test results.

| Specimen | Vertical Average Load (kN) | First Major crack | | | Average Maximum load | | Ratio of Reinfor. to Unreinf. Strengths | Ratio of increase of strength to total area of reinforce. (kN/m2) |
|---|---|---|---|---|---|---|---|---|
| | | Thickness (mm) | Displ. (mm) | Load (kN) | Displ. (mm) | Load (kN) | | |
| MLC-00-CA-SF-01 | 104.0 | 0.70 | 0.80 | 103.9 | 5.25 | 145.9 | - | - |
| MLC-00-CA-SF-02 | 100.7 | 0.33 | 1.21 | 129.4 | 3.03 | 135.3 | - | - |
| **Average** | - | - | - | - | **4.14** | **140.6** | - | - |
| MLC-00-CA-FX-01 | 103.2 | 0.40 | 2.99 | 193.6 | 10.2 | 259.4 | 1.84 | 35.3 |
| MLC-00-CA-FX-03 | 101.9 | 1.00 | 3.04 | 161.5 | 9.90 | 229.6 | 1.63 | 39.6 |
| MLC-00-CA-FH-02 | 101.2 | 0.50 | 2.96 | 179.5 | 8.23 | 226.7 | 1.61 | 48.4 |
| MLC-00-CA-FH-04 | 100.6 | 0.50 | 2.98 | 156.4 | 9.41 | 220.2 | 1.57 | 66.9 |

## Unreinforced Walls

The two walls had a brittle failure, with a single wide diagonal crack. The hysteretic response of the walls is shown in Fig. 7 up to 10 mm of horizontal displacement. At that displacement level the walls had lost approximately 25% of their strength.

## Diagonally reinforced walls

The hysteretic response of the walls is shown in Fig. 8 up to failure. The two walls had a brittle failure, with several diagonal cracks. The failure mechanism was as follows: high compressive stress at the bottom ends of the walls due to in-plane bending of the walls damaged the bricks at that location; failure occurred when peeling stresses at the bottom end of a strip broke the previously damaged bricks (see Fig. 9) and the fabric delaminated in up to 50% of its length; then the strength dropped sharply.

## Horizontally reinforced walls

The hysteretic response of the walls is shown in Fig. 10 up to failure. Failure started as the bottom fabric strips begun to delaminate during the at one 14 mm displacement, producing a decrease of stiffness and strength of the walls. As the test went on to the next 14 mm cycle the strip continued delaminating and the strength of the walls decreased by more than 50%. After unloading, more than 80% of the strip had delaminated, the stiffness of the wall was very small, and the masonry below the second strip was highly damaged. There was never a sudden loss of strength, as in the diagonally reinforced walls.

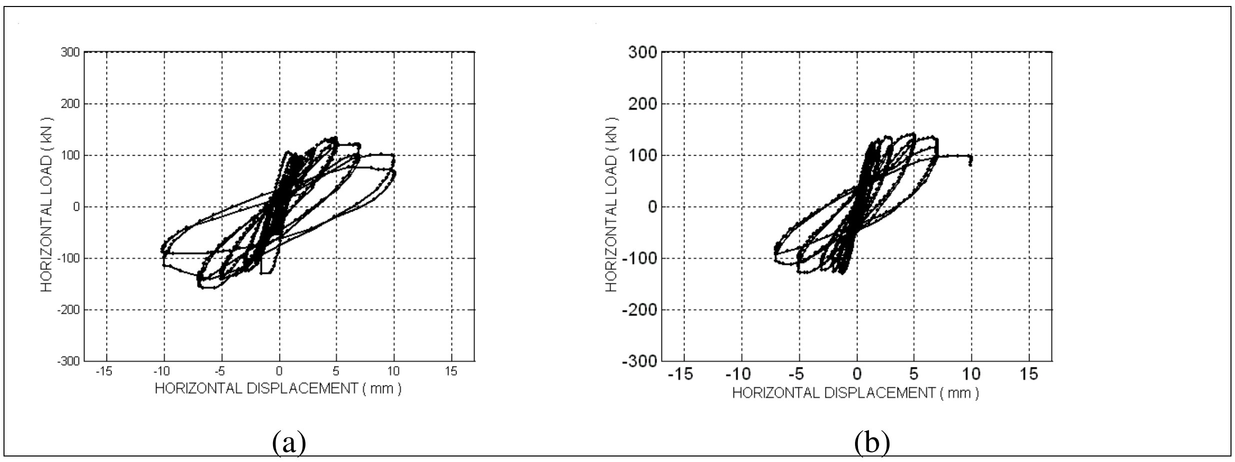



Figure 7. (a) MLC-00-CA-SF-01 hysteric curve. (b) MLC-00-CA-SF-02 hysteric curve.

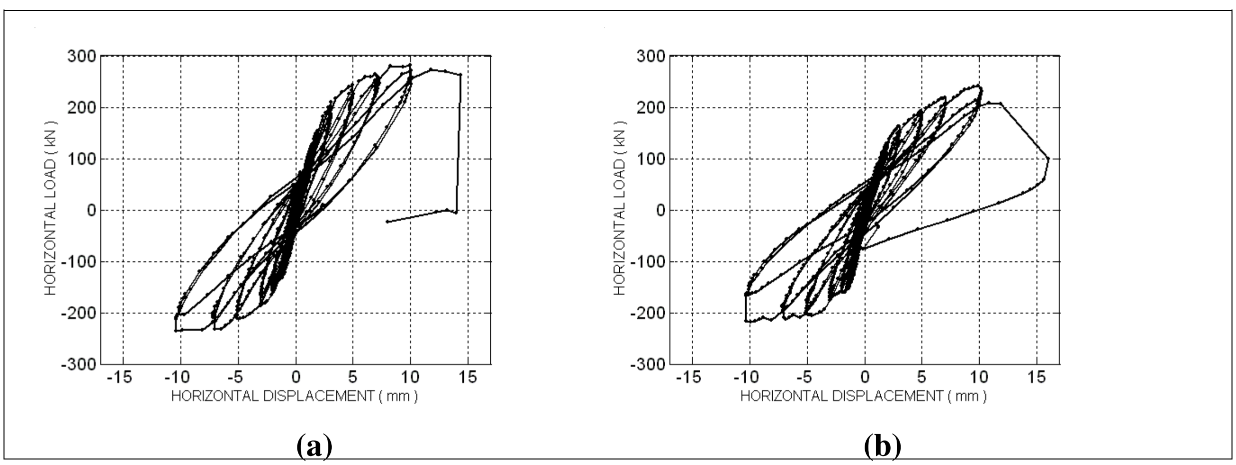



Figure 8. (a) MLC-00-CA-FX-01 hysteric curve. (b) MLC-00-CA-FX-03 hysteric curve.

Figure 9.  Failure mode of the DRM walls. The bottom bricks were previously damaged.

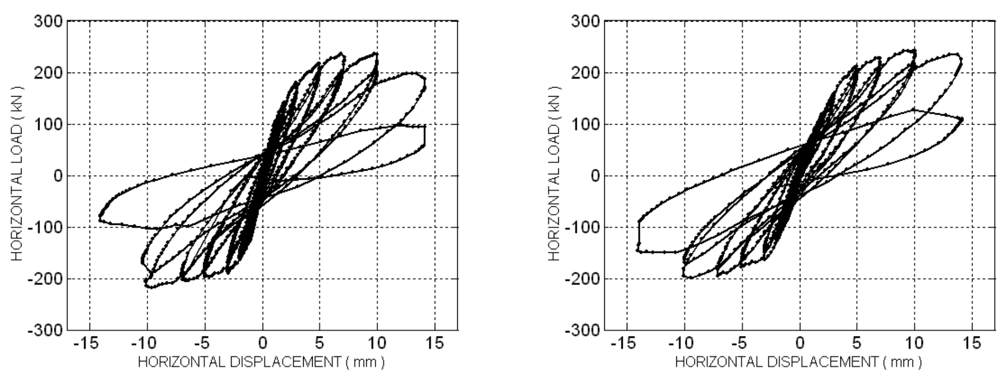


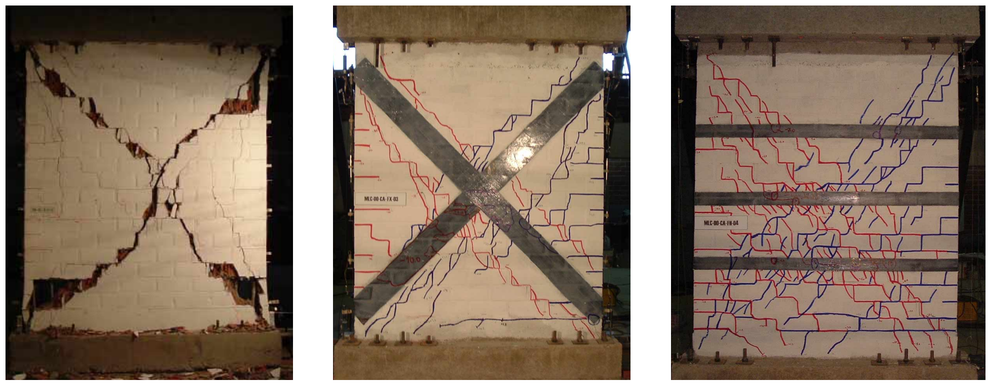

Figure 10.  (a) MLC-00-CA-FH-02 hysteric curve. (b) MLC-00-CA-FH-04 hysteric curve.

**Cracking**

In the reinforced walls the first major crack occurred at approximately 3 mm of lateral displacement, compared to only 1.2 mm average for the URM walls. Also, the load at which the major crack was observed increased from 120 kN in the URM walls to between 160 to 190 kN in the reinforced walls. The URM walls had one wide diagonal crack, the DRM walls had several cracks, and the HRM walls had the most spread cracks, as can be seen in Fig 11.

**Strength**

The DRM walls had an increase in strength of 63% and 84%, while de HRM walls had 57% and 61% increase of strength. In both cases, the increase was larger in the walls with a larger amount of reinforcement. The HRM walls were more effective in terms of increase of strength per amount of fabric used (see Table 4 for values). But in terms of reinforcement ratio, the DRM walls are more effective. The difference is due to the fact that in the HRM walls the reinforcement works for both directions of loading, while in the DRM walls only one diagonal is working in each direction of loading. Also, the displacement at maximum strength increased from approximately 5 mm in the URM walls to approximately 10 mm in the reinforced walls.



(a) (b) (c)

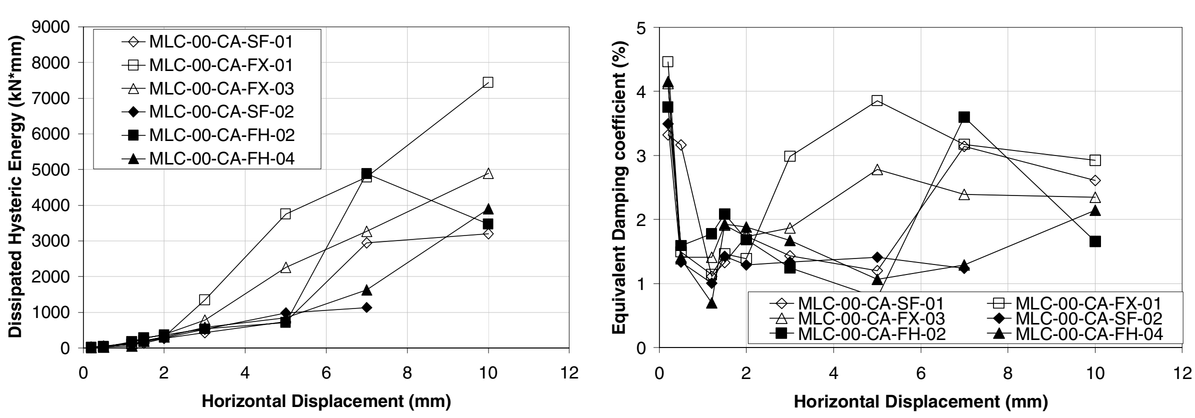
Figure 11. Crack pattern: (a) URM wall, (b) DRM wall, (c) HRM wall.

## Energy Dissipation

The energy dissipated was calculated as the area enclosed by a load cycle. The equivalent viscous damp coefficient was calculated as:

$$\xi_{eq} = E_H/(2*\pi*K_{.sec}\,\delta_{max}^{\;2}) \tag{2}$$

where $E_H$ is the hysteretic energy dissipated in one cycle, $K_{sec}$ is the secant stiffness in the cycle; and $\delta_{max}$ is the maximum displacement in the cycle. In Fig. 12 are shown the hysteretic energy and the equivalent viscous damp coefficient for each wall at the corresponding maximum nominal displacement of the first cycle. Only the diagonally reinforced walls had an important increase of energy dissipated per cycle, and it was larger for the wall with more reinforcement.




(a) (b)

Figure 12. (a) Dissipated hysteretic energy, (b) equivalent damp coefficient for the first cycle.

## Strength Calculation

To calculate the increase of strength a very simple model is proposed. From the force system in Fig. 13 it is clear that the strength of the reinforced wall is:

$$V = V_m + T_f * \cos\alpha \tag{3}$$

where $V_m$ is the strength of the masonry at the compression zone and $T_f$ is the strength of the fabric reinforcement. It is assumed that $V_m$ is equal to the strength of the URM walls. The difficulty is to predict $T_f$. The failure mechanism of the reinforced walls begins with the delamination of the reinforcement. As part of this investigation tests of the bond of fabric to clay bricks were performed and will be reported elsewhere. The average bond strength per unit width of fabric was found to be 0.25 kN/mm. Therefore, it is assumed that the strength of the fabric is controlled by delamination. In Table 4 are the average measured strengths and calculated strengths. It can be seen that the model is very accurate for the strength of the DRM walls, but overestimates the strength of the HRM walls. The horizontal strips are not subjected to the same stresses, which is confirmed by the fact that only the bottom strip delaminated.

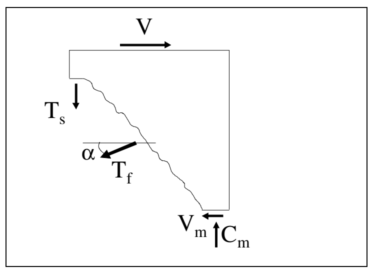



Figure 13. Force system in a cracked wall.

Table 4. Comparison of measured to calculated strengths.

| Specimen | Average Strength (kN) | Calculated Strength (kN) | Ratio of Measured to calculated Strength |
|---|---|---|---|
| MLC-00-CA-FX-01 | 259.4 | 247.6 | 1.05 |
| MLC-00-CA-FX-03 | 229.6 | 221.8 | 1.04 |
| MLC-00-CA-FH-02 | 226.7 | 365.6 | 0.62 |
| MLC-00-CA-FH-04 | 220.2 | 290.6 | 0.76 |

## Conclusions

The contribution of two different configurations of FRP reinforcement to the in-plane shear response of hollow clay brick walls was experimentally investigated. The conclusions are summarized as follows:

1. URM walls with externally reinforced with bonded fabric increases the shear strength of the walls, the maximum displacement before failure, and the displacement and load of first major crack. Increase of strength of 60 to 80% was observed.
2. The walls reinforced showed several spread cracks, with small thickness. The horizontal reinforcement was more effective in spreading the cracks.
3. The DRM walls had a brittle failure with sudden loss of strength, while the HRM walls showed a less brittle failure.
4. The DRM walls showed an increase of energy dissipation, which was not observed in the HRM.
5. High compressive stresses in the masonry produced de-bonding of FRP reinforcement.
6. It is necessary to perform more tests to improve the models to predict the strength of the reinforced walls.

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