CFRP RETROFIT OF MASONRY WALLS

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Abstract

This study is concerned with the seismic retrofit on unreinforced hollow concrete masonry (CMU) walls using carbon fiber reinforced polymer (CFRP) composites. In order to investigate the possibility of using FRP composites as a retrofit material, six 1219 mm by 2438 mm masonry walls were tested before and after composite retrofit. Three of the walls (shear specimens) were loaded with in-plane shear forces, and three of the walls (bending specimens) were subjected to out-of-plane bending. Both of these wall types were retrofitted with three different composite laminates.

The retrofitted shear specimens reached a maximum lateral load of 41.6 kN, a strength increase of 1100%. All of these specimens lost their load carrying capacity due to extensive damage near the supports, well before the composite material reached its ultimate strength. The bending specimens reached a maximum of 179.6 kN, which represented an increase of 3100% over the baseline specimens. These bending specimens behaved like traditional composite sandwich panels, which take advantage of the high tensile/compressive strength material at the face of the inner (masonry) core. The experimental results showed that the FRP laminates significantly increased the in-plane shear and out-of-plane bending capacity of precracked unreinforced hollow masonry walls. Since both wall faces were retrofitted with multiple composite layers, the stress level in the FRP material was well below its ultimate values, clearly indicating that for these tests the masonry governed the results. In addition, an analytical procedure was developed to predict the behavior of masonry walls retrofitted with composite laminates.

Introduction

Methods for seismic rehabilitation of masonry structures include the use of shotcrete, coatings for unreinforced masonry (URM) walls, grout injection, steel bracing and stiffening elements (FEMA 1997). Research on retrofit techniques for masonry elements was conducted by Seible et al. (1990). A five-story building model was repaired successfully using carbon fiber composite materials. The dynamic characteristics of masonry bearing and shear walls have been analyzed experimentally by Al-Chaar & Hassan (1999). The glass FRP overlays enhanced the wall's shear capacity and overall strength.

Composite materials have been used for the seismic rehabilitation of URM walls in studies performed by Ehsani & Saadatmanesh (1996) and by Ehsani et al. (1997). The composites were externally attached to masonry elements to increase the members' flexural and shear capacity. An experimental and analytical study was performed on masonry walls retrofitted using FRP laminates by Triantafillou (1998). Gilstrap & Dolan (1998) investigated the out-of-plane bending of masonry walls reinforced with composite tapes. The performance of unreinforced masonry walls strengthened with glass and carbon composites was evaluated by Marshall et al. (1999). In each of these studies, considerable strength was gained through the use of FRP.

Experimental Program

The objective of this study was to experimentally and analytically investigate precracked unreinforced hollow CMU walls retrofitted with composite laminates (using three different lamination schedules), subjected to in-plane shear (shear specimens) and out-of-plane bending (bending specimens) loads.

Six identical 1219 mm by 2438 mm masonry walls were constructed and tested, and then retrofitted with composites and retested. 194 mm wide CMU blocks were used (the average compressive strength of the units was 10.3 MPa) with Type S mortar. In order to identify the walls' existing capacity, each wall was initially pretested up to the cracking point (baseline tests). Three of the walls were loaded with in-plane cyclic loads, and three of the walls were subjected to out-of-plane four point bending.

The cyclic loads were applied in both directions three times, and then increased to the next load step. Displacement transducers were used to monitor the in-plane and out-of-plane deformations of the specimens at several locations throughout the masonry walls. Strain gages were attached to the FRP laminates to record the stress level in the composite material on the specimen surface.

The boundary condition for the shear test setup modeled a cantilever wall with fixed conditions at the bottom. The wall in the bending setup however, was pin-supported at the top and the bottom, using a reaction column and special roller supports. In order to create a more severe condition of low axial load in a wall system, no additional axial force was added to the masonry walls, except its own weight.

Baseline Specimens

Three shear wall specimens were tested in the as-built condition. The first wall was loaded monotonically, and reached a maximum lateral load of 7.1 kN. Failure was determined as the point when due to extensive mortar joint damage the wall lost its lateral load resisting capacity (as shown in Figure 1). Large cracks developed in the mortar bed joints at the lower section of the shear wall specimen. This failure mode was typical for all the baseline shear specimens.

The loading schedule for the other two shear specimens followed a cyclic loading up to the failure point, which occurred at an average lateral load of 3.6 kN (see Figure 2). It is important to note, that this peak load was only half of the force reached in the first test. This suggests that a monotonic load results in less damage in an unreinforced concrete masonry wall than a cyclic load with stress reversal.

Similarly to the shear specimens, one flexural wall was loaded monotonically, and two were tested with a cyclic load. The behavior of Specimen 1 was close to linear, but once the first crack initiated around the wall's mid-height, the specimen failed at a peak lateral load of 6.4 kN, and at a maximum horizontal deflection of approximately 2.54 mm. The cyclic force used for the other two specimens was gradually increased from 1.8 kN up to the failure point with a 0.9 kN load increment. Even though the walls reached a horizontal deflection of 2.54 mm, their lateral load capacity was lower. As it can be seen in Figure 3, the peak lateral load was only 4.8 kN, proving again that a specimen when loaded in stress reversal looses its stiffness significantly as compared to a monotonically loaded wall.

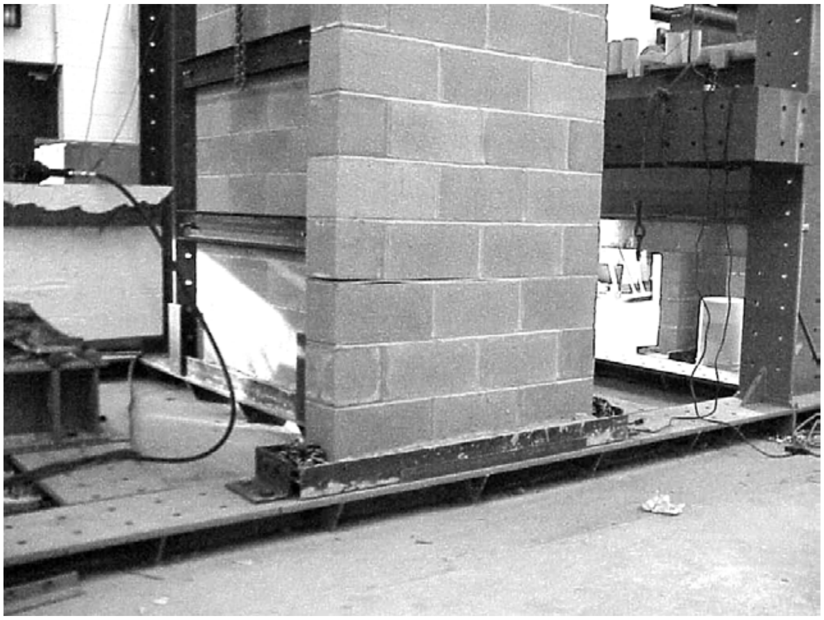

Figure 1. In-plane Baseline Shear Specimen at Failure

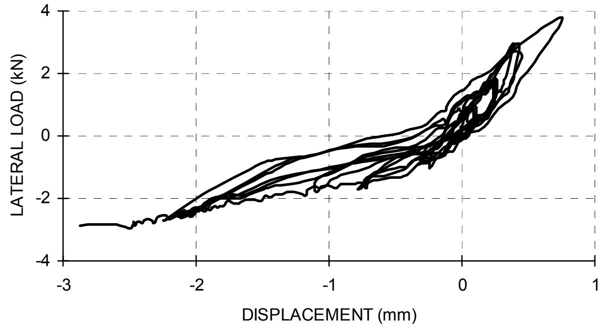

Figure 2. Shear Baseline Specimen Results

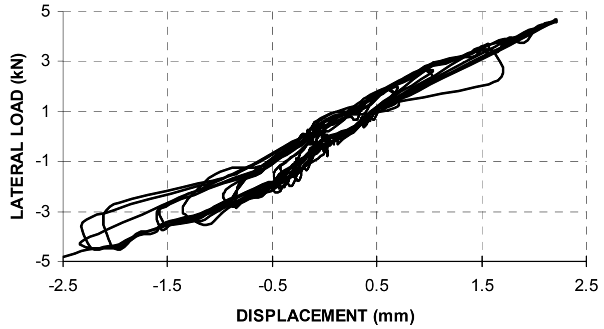

Figure 3. Bending Baseline Specimen Results

Retrofitted Specimens

Unreinforced masonry walls subjected to seismic forces behave in a very brittle way, and fail with little or no warning. By strengthening such a non-ductile structural element with composites (linear materials), the member's strength characteristics are considered rather then its ductility properties. After each wall was carefully removed from the loading frame using a special lifting system, the surface of the specimens was prepared using a wire brush, then vacuumed. To repair the walls, FiberBond™ composite laminates were applied to both sides of the samples.

Factors that are considered in a masonry wall retrofit design are, among others, the height-to-thickness and height-to-width ratios, the level of axial load, and the capacity and drift demand. Similarly to any orthotropic material, however, the effectiveness of the composite retrofit also depends on the orientation of the fibers. A [±45] layout is the most effective (although not always the most practical) to carry shear forces in a shearwall. A laminate aligned with the height of the wall (i.e. a [0_2] layout) is optimal for out-of-plane bending loads. Finally, a [0/90] laminate will provide an efficient method to strengthen walls supported on all four edges and subjected to two-way bending. To identify the effectiveness of all three layouts, each of them were applied and analyzed individually.

The test setup for the in-plane retrofitted shear specimens was identical to the baseline tests. Strain gages were positioned in the maximum stress zones, and were aligned in the direction of the fibers. The shear wall with the [±45] composite laminate reached a peak lateral load of 41.6 kN and a maximum horizontal deformation of 12.5 mm (see Figure 4). Failure occurred due to extensive damage at the base of the wall. This was clearly the result of excessive masonry shear and anchor stresses developed at the bottom of the wall, which exceeded the wall's capacity, even though the first masonry course was fully grouted with concrete, and shear studs were inserted in the cells (see Figure 5). The peak tensile stress in the composite laminate reached only 0.045%, only a fraction of the composite's ultimate strain of 1.5%.

The [0_2] specimen reached a peak load of 36.7 kN with a corresponding lateral deflection of 18.5 mm. Part of this deflection however, resulted from the wall's uplift and anchor failure. The apparent double stiffness observed during the test was due to the fact that once a large crack developed at the bottom of the wall, additional anchors were added to extend the testing a few more cycles. Since this shear specimen was tested first, the other two retrofitted shear walls received these additional anchors prior to testing. Once again, the strain in the composite was negligible compared to its capacity.

The [90/0] specimen failed at a lateral load of 33.6 kN and a horizontal deformation of 17.3 mm. The maximum composite strain reached 0.07%. Even though this specimen failed at the lowest lateral load level, it still showed a significant improvement compared to the baseline shear specimens (3.6 kN).

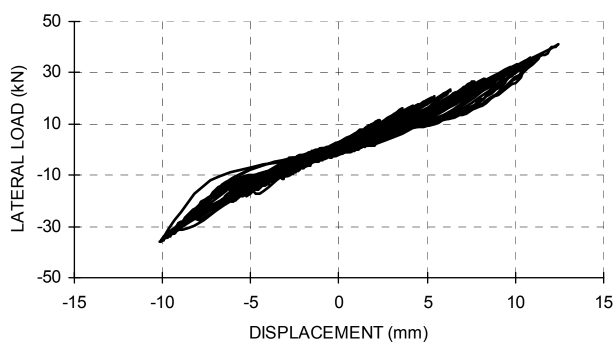

Figure 4. Retrofitted Shear Specimen Result

Figure 5. Retrofitted Shear Specimen at Failure

The test setup for the retrofitted bending specimen test was identical to the one described for the baseline specimens. Due to an unexpectedly high load reached during the first retrofitted specimen test, the loading device was damaged and was replaced with a substantially stronger steel member. The load-deformation curve for the wall with a [0_2] composite retrofit is shown in Figure 6. The peak lateral load of 168.5 kN represented an increase of 3400% over the baseline specimen, a result that proves the superior behavior of sandwich composite beams. The maximum strain readings in the composite fiber reached 0.17%, close to one-ninth of its ultimate capacity.

The wall with the [0/90] composite layout reached a 179.6 kN lateral load, and a maximum wall mid-height deformation of 16.8 mm. The peak tensile strain in the fiber was 0.32%. All of these results are very similar to the ones recorded for the [0_2] retrofitted wall, except, the strain level in the composite material. The strain doubled for the latter case to 0.32% for the same lateral load level, which makes sense if one considers that only half of the laminate added strength to the wall. As expected, the [±45] laminates provided the least wall strengthening. The wall failed at a 135.7 kN load and deformations over 24.4 mm.

Failure mode for the retrofitted bending specimens was due to extensive shear damage in the masonry wall initiated just outside the loading points. Initial diagonal cracking later propagated during the test, then extended into the composite-masonry interface causing FRP delamination. Ultimately, the masonry units inside the wall crumbled, and suddenly lost its lateral load carrying capacity (see Figure 7). There was so much damage in the wall that the walls during removal from the test setup disintegrated.

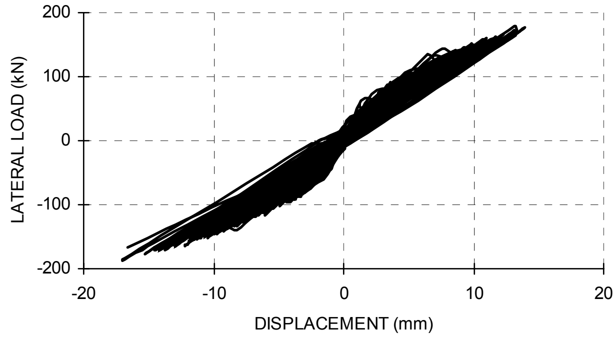

Figure 6. Retrofitted Bending Specimen Results

Figure 7. Retrofitted Bending Specimen at Failure

Analytical Results

Shear Specimens

As shown in Figures 1 and 5, the shear specimens were fixed at the bottom of the wall, and can be analyzed as a fixed wall, with no axial load present, and subjected to a cyclic lateral load at the top of the wall. The analytical equations from ACI 440 (2001) and from ICBO AC125 (2001) were modified and used in the present study to correlate experimental data with analytical results. Both of these documents provide equations for beams and/or walls subjected to shear and retrofitted with FRP composites. Equation 1 considers the laminate properties, as well as the wall sectional characteristics to estimate the FRP contribution to the wall shear capacity:

$$V_f = n_f t_f E_f \varepsilon_f \frac{w_f}{s_f} (\sin^2 \alpha) d_f \varphi \qquad (1)$$

where n_f = number of fiber layers oriented at an angle α with respect to the wall axis; t_f = composite layer thickness; E_f = FRP modulus of elasticity; ε_f = expected or measured strain level in the composite; w_f = width of the composite laminate; s_f = horizontal spacing between composite strips; d_f = width of the wall (not to exceed the wall height); and φ = reduction factor that considers single sided or double sided FRP applications (only the latter case was tested in this project).

No composite damage (rupture, delamination, etc…) was observed, and the stress level was well below the FRP capacity, some of the analytical results were reasonable, others however, were not so close to the experimental data. With Equation 1, and using the measured shear capacity increase by FRP, the composite strain can be calculated and compared with the maximum strain recorded during testing. For the [0/90] laminate applied to both sides, the strain was found to be ε_f = 0.072% (or 0.00072) using the following information: V_f = 33.36 kN; n_f = 2; α = 45^0; t_f = 0.584 mm; E_f = 64.81 GPa; w_f = s_f full wall coverage; d_f = 1219 mm; and φ = 0.5. This compares well with the 0.070% measured strain.

Bending Specimens

Due to the limited space available in this paper, a full analysis on the bending tests will not be demonstrated here. The analysis of a doubly reinforced masonry wall subjected to out-of-plane bending would involve the finding of the neutral axis, than the evaluation of tension forces in the FRP on one side of the wall, and the calculation of compression forces in the masonry unit as well as in the FRP on the other side of the wall. As expected, the compression stresses in the FRP were 2-to-3 times lower than the tensile stresses in the composite on the opposite side within the same load cycle. This demonstrates again the effectiveness of FRP composites in tension, and the significance of contribution by masonry in compression.

Conclusions

The experimental results showed that the FRP laminates significantly increased the in-plane shear and out-of-plane bending capacity of precracked unreinforced hollow masonry walls. Since both wall faces were retrofitted with multiple composite layers, the stress level in the FRP material was well below its ultimate values, clearly indicating that for these tests the masonry governed the results. In addition, as a result of using an improved adhesive material, no composite delamination was observed.

Acknowledgement

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