OUT-OF-PLANE BEHAVIOR OF URM WALLS
STRENGTHENED WITH FRP SYSTEMS

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Abstract
Fiber reinforced polymer (FRP) composites in the form of laminates or bars can provide viable solutions for the strengthening of unreinforced masonry (URM) walls subjected to overstresses. This paper summarizes the experimental results of investigations conducted by the University of Missouri-Rolla on the flexural behavior of URM walls strengthened with FRP systems. Thirty URM specimens (concrete and clay masonry) were tested. Twenty-five specimens were tested using FRP laminates and the remaining five walls were strengthened using FRP bars. The specimens were strengthened with different amounts of reinforcement. In the case of the walls reinforced using FRP laminates, also the influence of the putty filler on the bond strength was investigated. The walls were tested under simply supported conditions.

1. Introduction
Structural weakness, overloading, dynamic vibrations, settlements, and in-plane and out-of-plane deformations can cause failure of unreinforced masonry (URM) structures. URM buildings have features that, in case of overstressing, can threaten human lives. These include unbraced parapets, inadequate connections to the roof, floor and slabs, and the brittle nature of the URM elements.
Fiber reinforced polymer (FRP) composites may provide viable solutions for the strengthening of URM walls subjected to in-plane and out-of-plane loads caused by high wind pressures or earthquakes. The use of FRP materials offers important advantages in addition to their mechanical characteristics and ease of installation. For example, disturbance to occupants is minimized and, during installation, there is a minimal loss of usable space. Furthermore, from the structural point of view, the dynamic properties of the structure remain unchanged because there is no addition of mass. For the case of stiffness, the designer may select not to affect it, so that there is no redistribution of forces.
This paper summarizes the experimental results of investigations conducted by the University of Missouri-Rolla on the flexural behavior of URM walls strengthened with FRP systems. The test specimens consisted of concrete and clay masonry panels strengthened with different amounts of FRP reinforcement to observe their improved
performance and the mode of failure. Two different strengthening techniques were used: FRP laminates and GFRP bars. In the case of the FRP laminates two types of FRP fabrics, glass FRP (GFRP) and aramid (AFRP), were used for the strengthening. In addition, the influence of the putty filler on the bond strength was investigated. The putty is used to fill small surface voids and to provide a leveled surface to which the FRP can be attached. Based on experimental evidence generated by these investigations and others, the paper provides criteria that can be used in the development of design guidelines when a masonry wall is assumed to be simply supported (i.e. arching mechanism is not present).

2. Experimental Programs

2.1. Test Matrices

2.1.1. Externally bonded laminates [1], [2]. Two different FRP systems, GFRP and Aramid FRP (AFRP) were installed by manual lay-up. A single strip was placed in different amounts along the longitudinal axis on the tension side: the strip widths ranged from 75 mm to 300 mm. Two different masonry units (concrete and clay), and two surface preparation methods (with or without putty filler) were investigated to account for different compressive strengths and surfaces. The putty filler is used to fill small surface voids and to provide a leveled surface to which the FRP can be attached. The surface preparation of all the masonry specimens built with clay units included the use of putty. This was because the clay brick wall surfaces exhibited more unevenness that those of concrete blocks. Table 1 presents the test matrix.

<table>
<thead>
<tr>
<th>Masonry Type</th>
<th>Series</th>
<th>FRP Fiber</th>
<th>Strip Width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>Concrete</td>
<td>COG</td>
<td>GFRP</td>
<td>COG-L3</td>
</tr>
<tr>
<td></td>
<td>COA</td>
<td>AFRP</td>
<td>COA-L3</td>
</tr>
<tr>
<td>Clay</td>
<td>CLG</td>
<td>GFRP</td>
<td>CLG-L3</td>
</tr>
<tr>
<td></td>
<td>CLA</td>
<td>AFRP</td>
<td>CLA-L3</td>
</tr>
</tbody>
</table>

2.1.2. NSM FRP bars [3], [4]. Five concrete masonry panels were strengthened with 6.25 mm-diameter and 9.37 mm-diameter sand-coated twisted Glass FRP (GFRP) bars in different amounts (one, two or three bars) with a spacing of 20, 30 and 60 cm; the reinforcement was encapsulated in a square groove by using an epoxy-based paste as embedding material. The dimension of the groove has been taken equal to 1.5 times the diameter of the bar. Table 2 presents the test matrix. Thus, a total of five series of walls were considered in these two experimental programs: COG-Lx, COA-Lx, CLG-Lx, CLA-Lx and COG-Rxy. The first two characters in the code represent the type of masonry used, “CO” for concrete masonry and “CL” for clay masonry. The third character indicates the type of reinforcement: G for GFRP and A for
AFRP. The character following the dash sign can be “L” or “R” indicates the type of strengthening technique used: “L” for FRP Laminate and R for NSM GFRP bars. The number following the character “L” represents the width of the FRP laminate in inches. Thus, CLG-L5R is a clay masonry wall, strengthened with a GFRP laminate, having a width of 125 mm. The final character “R” indicates a test repetition. For the other kind of specimens the two numbers following the character “R” represent the diameter in eighth of an inches and the number of NSM Bars per specimen respectively. Thus COG-R31, refers to a concrete masonry panel, strengthened with one 9.37 mm-diameter GFRP bar embedded in epoxy-based paste.

Table 2. Test Matrix - GFRP Bars

<table>
<thead>
<tr>
<th>Code for Series CORG</th>
<th>Embedding material</th>
<th>Diameter(d) mm</th>
<th>Amount of bars</th>
<th>Space between two bars mm</th>
<th>Depth of the groove times of d</th>
</tr>
</thead>
<tbody>
<tr>
<td>COG-R31</td>
<td>Epoxy-based paste</td>
<td>9.525</td>
<td>1</td>
<td>600</td>
<td>1.5</td>
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<tr>
<td>COG-R32</td>
<td></td>
<td>9.525</td>
<td>2</td>
<td>300</td>
<td>1.5</td>
</tr>
<tr>
<td>COG-R33</td>
<td></td>
<td>9.525</td>
<td>3</td>
<td>200</td>
<td>1.5</td>
</tr>
<tr>
<td>COG-R22</td>
<td></td>
<td>6.350</td>
<td>2</td>
<td>300</td>
<td>1.5</td>
</tr>
<tr>
<td>COG-R23</td>
<td></td>
<td>6.350</td>
<td>3</td>
<td>200</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.2. Materials

2.2.1. Masonry. Tests were performed to characterize the engineering properties of the materials used in these investigations. The average compressive strengths of concrete and clay masonry obtained from the testing of prisms (ASTM C1314) were 10.5 MPa and 17.1 MPa, respectively. Type N mortar was used; standard mortar specimens were tested according to ASTM C109. An average value of 7.6 MPa at an age of 28 days was found.

2.2.2. FRP Systems. Tensile tests were performed on FRP laminates and bars to determine their engineering properties. The test results showed that the tensile strength of GFRP laminate was equal to 1690 MPa and the modulus of elasticity was 92.9 GPa. In the case of AFRP laminate, the tensile strength was 1876 MPa and the modulus of elasticity was equal to 115.2 GPa. The 6.25 mm-diameter GFRP bars had a tensile strength of 825 MPa and a modulus of elasticity of 40.8 GPa, while the 9.37 mm-diameter GFRP bars exhibited a tensile strength of 760 MPa and a modulus of elasticity of 40.8 GPa. Splitting tensile tests (ASTM C496) were performed on the epoxy-based embedding material used. The splitting tensile strength was found to be 16.31 MPa after 7 days and 18.54 MPa after 28 days.

2.3. Test Setup

For the five series the masonry specimens were tested under four-points bending (See Figure 1). Loads were applied by 50.8 x 609.6 x 12.7 mm (2 x 24 x ½ in.) steel plates to the external face of the wall. Their distance was 101.6 mm (4 in.) from the midspan. The loads were generated by means of a 12 ton hydraulic jack reacting against a steel frame.
Linear Variable Displacement Transducers (LVDTs) were positioned in the middle of the walls to measure the midspan deflection during the tests.

![Figure 1 Test Setup](image)

### 2.4. Test Results

The walls exhibited the following modes of failure: (1) debonding of the FRP reinforcement (laminate or bar), (2) flexural failure, i.e. rupture of the FRP reinforcement in tension (only observed in FRP laminates) or crushing of the masonry in compression, and (3) shear failure in the masonry near the support.

1. **FRP Debonding:** Due to shear transfer mechanisms at the interface masonry/FRP Reinforcement, debonding of the reinforcement from the masonry substrate may occur before flexural failure (see Figures 2a and 2b). Debonding starts from flexural cracks at the maximum bending moment region and develops towards the supports. Since the tensile strength of masonry is lower than that of the epoxy resins, the failure line is in the masonry. In the case of concrete masonry walls, part of the concrete block faceshell remained attached to the FRP bar or laminate.

2. **Flexural Failure:** after developing flexural cracks primarily located at the mortar joints, a wall failed by either rupture of the FRP laminate or masonry crushing. FRP rupture occurred midspan (see Figure 2c). The compression failure was manifested by crushing of mortar joints.

3. **Shear Failure:** cracking started with the development of fine vertical cracks at the maximum bending region. Thereafter two kinds of shear failure were observed: flexural-shear and sliding shear (see Figure 2d). The former was oriented at approximately $45^\circ$, and the latter occurred along a bed joint causing sliding of the wall at that location, typically, at the first mortar joint in walls heavily strengthened. In the flexural-shear mode, shear forces transmitted over the crack caused a differential displacement in the shear plane which resulted in FRP debonding.

Table 3 reports the test results. The experimental results have been expressed as a function of the amount of reinforcement, $\rho_f$, defined as $\text{Area}_{\text{FRP}}/(\text{WallWidth} \times \text{WallThickness})$.

Figure 3 shows the Moment vs. Deflection Curves for the five series. It may be observed that the strength and stiffness of the FRP strengthened walls increased dramatically when comparing them to a URM specimen.
Figure 2 Modes of Failure

Table 3. Test Results

<table>
<thead>
<tr>
<th>Code</th>
<th>$R_f$ ($x10^4$)</th>
<th>$M_{exp}$ (kN-m)</th>
<th>Failure Mode</th>
<th>Code</th>
<th>$R_f$ ($x10^4$)</th>
<th>$M_{exp}$ (kN-m)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>COG-L3</td>
<td>5</td>
<td>2.05</td>
<td>D</td>
<td>CLG-L5R</td>
<td>8</td>
<td>5.37</td>
<td>R</td>
</tr>
<tr>
<td>COG-L3R</td>
<td>5</td>
<td>3.22</td>
<td>D</td>
<td>CLG-L7</td>
<td>11</td>
<td>6.58</td>
<td>D</td>
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<tr>
<td>COG-L5</td>
<td>8</td>
<td>3.33</td>
<td>D</td>
<td>CLG-L7R</td>
<td>11</td>
<td>7.20</td>
<td>D</td>
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<tr>
<td>COG-L5R</td>
<td>8</td>
<td>5.37</td>
<td>D</td>
<td>CLG-L9</td>
<td>14</td>
<td>6.94</td>
<td>S-S</td>
</tr>
<tr>
<td>COG-L7</td>
<td>11</td>
<td>3.74</td>
<td>D</td>
<td>CLG-L12</td>
<td>19</td>
<td>6.16</td>
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</tr>
<tr>
<td>COG-L9</td>
<td>14</td>
<td>5.23</td>
<td>F-S</td>
<td>CLA-L3</td>
<td>4</td>
<td>2.94</td>
<td>D</td>
</tr>
<tr>
<td>COG-L12</td>
<td>19</td>
<td>6.06</td>
<td>F-S</td>
<td>CLA-L5</td>
<td>6</td>
<td>5.23</td>
<td>R</td>
</tr>
<tr>
<td>COA-L3</td>
<td>4</td>
<td>2.54</td>
<td>D</td>
<td>CLA-L7</td>
<td>9</td>
<td>6.13</td>
<td>D</td>
</tr>
<tr>
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<td>6</td>
<td>3.57</td>
<td>D</td>
<td>CLA-L9</td>
<td>11</td>
<td>8.45</td>
<td>D</td>
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<tr>
<td>COA-L7</td>
<td>9</td>
<td>4.66</td>
<td>F-S</td>
<td>CLA-L12</td>
<td>15</td>
<td>5.90</td>
<td>S-S</td>
</tr>
<tr>
<td>COG-R31</td>
<td>12</td>
<td>1.56</td>
<td>D</td>
<td>COA-L9</td>
<td>10</td>
<td>5.25</td>
<td>F-S</td>
</tr>
<tr>
<td>COG-R32</td>
<td>24</td>
<td>3.93</td>
<td>S</td>
<td>COA-L12</td>
<td>15</td>
<td>6.33</td>
<td>F-S</td>
</tr>
<tr>
<td>COG-R33</td>
<td>36</td>
<td>5.57</td>
<td>S</td>
<td>CLG-L3</td>
<td>5</td>
<td>3.23</td>
<td>D</td>
</tr>
<tr>
<td>COG-R22</td>
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<td>1.68</td>
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<td>5</td>
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<td>R</td>
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<tr>
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<td>2.27</td>
<td>D</td>
<td>CLG-L5</td>
<td>8</td>
<td>4.89</td>
<td>D</td>
</tr>
</tbody>
</table>

D = FRP Debonding, R = FRP Rupture, F-S = Flexural Failure, S-S = Sliding Shear
Considering the Masonry Standards Joint Committee recommendations [10], the nominal moments at cracking for the concrete specimens can be estimated as 0.45 kN-m, whereas for the clay specimens this value is 0.95 kN-m. This indicates that depending on the amount of FRP, increments ranging from 4 to 14 times of the original masonry capacity were achieved. Since masonry possesses a significant amount of variability attributed to labor and materials, this range of values should be taken simply as a reference.

![Diagram](image_url)

**Figure 3. Moment vs. Deflection**

The test results show a clear and consistent pattern. Up to cracking the walls behaved almost in linear fashion. Initial cracking occurred at the interface of mortar and masonry for concrete masonry and in the mortar joint itself for clay masonry. Initial cracking was delayed due to the presence of FRP reinforcement. Following this, cracking at the adjacent
joint occurred until almost every joint in the high moment bending area was cracked. After cracking, the flexural stiffness is a function of the amount of FRP. A degradation of stiffness that is larger in walls with high amount of FRP reinforcement is observed. In this phase of the test, the cracks widen until the failure occurs.

3. Basis for a Design Approach

Of the three modes of failure described, the results obtained in this study and in those shown in the literature [5], [6], [7], [8] suggest that the controlling mode is mostly debonding of the FRP laminate. If a large amount of FRP is provided, shear failure may be observed.

The lower limit ratio $M_{\text{experimental}} / M_{\text{theoretical}}$ for non-puttied masonry surfaces can be safely take as 0.45; whereas for puttied surfaces this value can be 0.65 [1], [2]. In addition, it was defined a reinforcement ratio $\omega_f$, expressed as $\rho_f E_f / f_m (h/t)$, for masonry walls strengthened with a variety of FRP reinforcement ($E_f$ is the modulus of elasticity of FRP, $f_m$ is the masonry compressive strength, and $h/t$ is the wall slenderness ratio). The theoretical flexural capacity of an FRP strengthened masonry wall can be determined based on strain compatibility, internal force equilibrium, and the controlling mode of failure. Theoretical flexural capacity (i.e. optimum capacity) of the strengthened walls was estimated based on the assumption that no premature failure due to debonding or shear could occur. This means that either rupture of the laminate or crushing of masonry would control the wall behavior. For simplicity and similarly to the flexural analysis of RC members, a parabolic distribution was used for compressive stresses in the computation of the flexural capacity of the strengthened walls. According to MSJC [11] the maximum usable strain $\varepsilon_{\text{mu}}$ was considered to be 0.0035 mm/mm (in./in.) for clay masonry, and 0.0025 mm/mm (in./in.) for concrete masonry. The tensile strength of masonry was neglected.

It was shown that the index $\omega_f$ may be limited to 0.60 to prevent the occurrence of shear failure. Figure 4 and 5 illustrates the relationship between the experimental-theoretical flexural capacity ratio, and the reinforcement ratio $\omega_f$ for URM specimens strengthened with FRP systems. Figure 5 suggests that the lower limit ratio $M_{\text{experimental}} / M_{\text{theoretical}}$ for NSM bars can be taken as 0.35. In addition, $\omega_f$ limited to 0.60 to prevent the occurrence of shear failure is still valid even in the case of NSM bars. These considerations can be taken into account for the implementation of a design methodology.

Since the flexural capacity is dependant of the strain developed in the laminate, it is reasonable to express the effective strain in the laminate, $\varepsilon_{fe}$, as the product $\kappa_m \varepsilon_{fu}$, where $\kappa_m$ is the bond dependent coefficient and $\varepsilon_{fu}$ is the design rupture strain of FRP. Thus, the effective strain in the FRP laminate, $\varepsilon_{fe}$, is limited by the strain controlled by debonding:

$$\varepsilon_{fe} \leq \kappa_m \varepsilon_{fu}$$

FRP Laminates, if putty is used : $\kappa_m = 0.65$
FRP Laminates, if putty is not used: $\kappa_m = 0.45$
FRP Bars: $\kappa_m = 0.35$
These limits are valid for the case of walls not subjected to sustained load. In walls under sustained load such as retaining or basement walls, creep rupture considerations need to be taken into account. Thus, for the case of GFRP, $\kappa_m$ would be 0.20 in both laminates and bars [12].

![Graph](image1)

(a) Concrete Masonry (Without Putty)

![Graph](image2)

(b) Clay Masonry (With Putty)

Figure 4. Influence of Amount of FRP Reinforcement (Laminates)

![Graph](image3)

Figure 5. Influence of Amount of FRP Reinforcement (Bars)

4. Conclusions

The following conclusion can be drawn from these experimental programs:

1. Flexural strengthening with FRP systems has been proven to remarkably increase of flexural capacity (from 2 to 14 times), strength and pseudo-ductility of URM walls.
2. The test results made possible to identify three basic modes of failure. One, shear failure, related to the parent material (i.e. masonry); and two associated with the reinforcing material, debonding and flexural failure (i.e. rupture of FRP or crushing of the masonry). For large amounts of reinforcement (i.e. $\omega_f$ larger than 0.60), shear failure was observed to be the controlling mode. For other reinforcement ratios, either FRP rupture or debonding was observed, being the latter the most common.
3. In the case of strengthening with FRP laminates, the presence of putty on the masonry surface allows a better bond and thus increases the improved capacity given by the reinforcement. In this case, the failure mode may shift from FRP debonding to FRP rupture.
4. Based on experimental data showed in the present investigation and others, it is recommended to consider the maximum usable strain in the FRP Laminates as...
0.45ε_{fu} for non-puttied surfaces and 0.65ε_{fu} for puttied surfaces. In the case of NSM GFRP bars the maximum usable strain can be taken as 0.35ε_{fu}.

5. Acknowledgements

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