STRUCTURAL PERFORMANCE OF BRICK WALLS STRENGTHENED WITH COMPOSITE LAMINATES

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Extensive damage to the exterior and interior masonry walls of the municipal building left it unusable. The reinforced concrete frame was moderately damaged in localized areas.
Nuestra Senora de Los Remedios Church in Cholula, Puebla.
OBJECTIVE

- Evaluate Out-of-plane Structural Behavior of Red Brick Walls Strengthened With FRP Laminates,

- Develop Simplified Procedures for Design and Analysis of FRP Strengthened Walls
Experimental Program

- Characterization of Unit, Prism and Mortar Used in Fabricating Wall Specimens,
- Evaluating the Strength and Mode of Failure of Un-strengthened As-built Specimens,
- Evaluate the Structural Performance of Carbon/epoxy Retrofitting System, and
- Evaluate the Structural Performance of E-glass/epoxy Retrofitting System
Individual Brick Test

Common Red Clay Bricks (Castaic)
### Common Red Clay Bricks (Castaic) Test Results

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Dimensions (B X W X D)</th>
<th>Ultimate Compressive Load, kips [kN]</th>
<th>Compressive Strength, ksi [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-BR1</td>
<td>8” X 4” X 2 1¼” [20.32 cm X 10.16 cm X 5.72 cm]</td>
<td>119.70 [532.43]</td>
<td>3.74</td>
</tr>
<tr>
<td>N-BR2</td>
<td>Same</td>
<td>118.10 [525.31]</td>
<td>3.69</td>
</tr>
<tr>
<td>N-BR3</td>
<td>Same</td>
<td>110.27 [490.48]</td>
<td>3.45</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>116.022 [516.07]</td>
<td>3.627 [25.00]</td>
</tr>
</tbody>
</table>
Brick Prism Test

- Average Mortar thickness (measured): 0.25”
- Mortar Type: S-mortar
- Prism Overall Dimensions: 8” X 4” X 7 ¼”
- Prism Ultimate Load: 90,570 lb
- Bearing Area: 32 square inches
- Calculated Compressive Strength: 2.33 ksi [16.06 MPa]
TEST SETUP

Wall Specimen

LVDT’s

Composite Laminates

Uniform Water Pressure

Computer Control Unit

Pressure Transducer
Un-strengthened (As-Built) Wall Specimen Ultimate Failure Mode
Control (Unreinforced) Wall Specimen
Carbon/Epoxy Unidirectional $[0]_2$ Wall Specimen
Cohesive failure of both Mortar Line and Red Bricks

Carbon/Epoxy Unidirectional $[0]_2$ Wall Specimen
Carbon/Epoxy Unidirectional \([0]_2\) Wall Specimen
Carbon/Epoxy Unidirectional $[0]_2$ Wall Specimen
Carbon/Epoxy Cross-ply \([0^\circ/90^\circ]\) Wall Specimen
Carbon/Epoxy Cross-ply \([0^\circ/90^\circ]\) Wall Specimen

![Graph of Carbon/Epoxy (0°/90°)\(_2\) showing strain vs. load for different specimens SG-1 to SG-8.](image-url)
Carbon/Epoxy Cross-ply

[0°/90°] Wall Specimen
E-glass/Epoxy
Unidirectional $[0^\circ]_3$
Wall Specimen
E-glass/Epoxy
Unidirectional
$[0^\circ]_3$ FiberBond
Strengthened Wall Specimen
E-glass/Epoxy Unidirectional $[0^\circ]_3$ FiberBond Strengthened Wall Specimen (Ultimate)
E-glass/Epoxy Unidirectional $[0^\circ]_3$ FiberBond Strengthened Wall Specimen
Summary of Experimental Results
THEORTICAL MODELING

The analytical modeling used in this study is based on a simple section analysis procedure identical to that used in the analysis of RC concrete beams. However, new parameters have been adopted for the masonry wall based on available experimental data.
Stress-Strain Model for Brick-Mortar Blocks in Compression
The first part of the analysis is to define the material properties. The stress-strain curve for brick-mortar blocks under compression consists of two distinct regions:

- a parabolic relationship up to the maximum compressive strength, $f_m$, and a linear descending branch up to the ultimate compressive strain, $\varepsilon_{mu}$.
- The first region of the stress-strain curve is assumed polynomial,
The four unknowns in Eq. (1) are determined from the following boundary conditions:

i. \( f_m = 0.0 \) at \( \varepsilon_m = 0.0 \)

ii. \( f_m = f'_m \) at \( \varepsilon_m = \varepsilon_{mo} \)

iii. \( df_m/d\varepsilon_m = E_m \) at \( \varepsilon_m = 0.0 \)

iv. \( df_m/d\varepsilon_m = 0.0 \) at \( \varepsilon_m = \varepsilon_{mo} \)
Table (1): Mechanical Properties for FRP Laminates

<table>
<thead>
<tr>
<th>FRP System</th>
<th>Thickness/Layer (inch)</th>
<th>Tensile Modulus, $E_j$ (ksi)</th>
<th>Tensile Strength, $f_{ju}$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon/Epoxy</td>
<td>0.023</td>
<td>15060</td>
<td>180.7</td>
</tr>
<tr>
<td>E-glass/Epoxy</td>
<td>0.045</td>
<td>2679</td>
<td>61.6</td>
</tr>
</tbody>
</table>
The equations of the stress-strain curve have been determined to be:

- For $0 < \varepsilon_m < \varepsilon_{mo}$:

\[ f_m = E_m \varepsilon_m \left[ 1 - \frac{1}{n} \left( \frac{\varepsilon_m}{\varepsilon_{mo}} \right)^{n-1} \right] \]

\[ n = \frac{E_m \varepsilon_{mo}}{E_m \varepsilon_{mo} - f_m} \]
• For $\varepsilon_{mo} < \varepsilon_m < \varepsilon_{mu}$:

$$f_m = f'_m - E_d (\varepsilon_m - \varepsilon_{mo})$$

$$E_d = \frac{0.5 f'_m}{(\varepsilon_{mu} - \varepsilon_{mo})}$$
The parameters of the stress-strain curve are:

\[ f'_m = 4500 \text{ psi}, \quad \varepsilon_{mo} = 0.002, \]
\[ \varepsilon_{mu} = 0.0035, \quad E_m = 2.8 \times 10^6 \text{ psi}, \]
and \[ f_{mf} = 0.5 f'_m. \]
- Tensile strength of the brick-mortar blocks is ignored,
- Tensile resistance of the FRP laminates can be neglected in the transverse direction,
- The area of the FRP laminates is enough for the failure of the specimen to be due to masonry crushing rather than fiber fracture.
- Plane section before bending remains plane after bending, and hence a linear strain distribution can be assumed along the section.
In order to proceed with section analysis, it is necessary to develop the parameters of the equivalent rectangular stress block shown in the above. By integrating the stress-strain curve for brick-mortar blocks in compression, these parameters can be determined as follows:
\[ \beta = 2 \left[ 1 - \frac{\int_{0}^{\varepsilon_{mu}} f_{m} \varepsilon_{m} d\varepsilon_{m}}{\varepsilon_{mu} \int_{0}^{\varepsilon_{mu}} f_{m} d\varepsilon_{m}} \right] = 0.88 \]

\[ \gamma = \frac{\int_{0}^{\varepsilon_{mu}} f_{m} d\varepsilon_{m}}{\beta f_{m} \varepsilon_{mu}} = 0.8 \]
## Comparison between Theoretical and Experimental Results

<table>
<thead>
<tr>
<th>Specimen Configuration</th>
<th>Experimental Maximum Load, $P_{u\text{-exp}}$ (tons)</th>
<th>Theoretical Maximum Load, $P_{u\text{-tho.}}$ (tons)</th>
<th>$P_{u\text{-tho}} / P_{u\text{-exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[0^\circ]_2$ Carbon/Epoxy</td>
<td>58.0</td>
<td>49.6</td>
<td>0.86</td>
</tr>
<tr>
<td>$[0^\circ/90^\circ]_1$ Carbon/Epoxy</td>
<td>47.0</td>
<td>38.95</td>
<td>0.83</td>
</tr>
<tr>
<td>$[0^\circ]_3$ E-glass/Epoxy</td>
<td>55.8</td>
<td>40.53</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Experimental results indicated that FRP composites can be significantly upgrade the out-of-plane flexural capacity of red brick walls up to 15 times the original strength of As-built walls.
The proposed simplified analytical approach has proven to be effective in predicting the ultimate capacity of retrofitted specimens.

- The proposed model provides a conservative prediction of the ultimate load, and hence it can be adopted for design FRP strengthened walls subjected to out-of-plan loads.
Cyclic Shear Test of Multi-Wythe Recycled Brick Red Wall

In progress
Evaluation of In-Plane behavior of Strengthened Masonry Walls

(In progress)
Prestressed RC Pipes FRP Strengthening In progress