BEHAVIOR OF FRP STRENGTHENED MASONRY WALLS UNDER OUT-OF-PLANE SEISMIC LOADING

Y.A. Al-Salloum*, T.H. Almusallam and S.H. Alsayed

Department of Civil Engineering, King Saud University,
P.O. Box 800, Riyadh 11421, Saudi Arabia. Email: ysalloum@ksu.edu.sa

ABSTRACT

The effectiveness and efficiency of fiber reinforced polymer (FRP) sheets in strengthening the concrete block walls subjected to out-of-plane seismic loadings has been investigated. Two concrete masonry wall specimens were cast for this purpose. One specimen was used as control (unstrengthened) and other was strengthened with GFRP sheets. These wall specimens were then tested under out-of-plane loadings and load carrying capacities were obtained and compared. Results of experimental observations are presented in the form of load-displacement curves and response envelopes. FRP strengthened wall showed a many fold increase in the strength with respect to unstrengthened control specimen. In order to predict load carrying capacity and failure modes of control and FRP strengthened masonry walls, simple analytical models are also proposed employing conventional assumptions of bending theory and force equilibrium conditions. The results indicate that there is an excellent agreement between predicted values and measured test results.

KEYWORDS

Masonry walls, seismic, URM, strengthening, repair, cyclic loads.

INTRODUCTION

World wide unreinforced masonry walls are employed as partitions in building frames. During earthquake these walls are highly vulnerable to failure due to their poor out-of-plane deformation capacity and load carrying capacity. To increase the out-of-plane deformation and load carrying capacities, use of epoxy bonded Fiber Reinforced Polymers (FRPs) in the form of sheets, strips or bars is modern way.

In the last two decades, some research has been conducted to study the effectiveness of FRP in strengthening URM walls against out-of-plane and/or in-plane loads caused by earthquakes or wind loads. Ehsani and Saadatmanesh (1996) studied the flexural and shear behavior of URM walls subjected to monotonic static load by testing small URM beam specimens. The URM beam specimens were strengthened using thin flexible E-glass fabrics. Three types of fabrics, i.e. ranging from lighter to stronger, were used. It was observed that the mode of failure in flexural test was governed by the strength of fabrics. Al-Saidy et al. (1996) examined the suitability of overlays bonded to the surface of solid clay bricks. The variables in the test included the strength of the fabric, fiber orientation and anchorage length. The specimens were tested under static loading. The results showed that the technique can significantly improve both the strength and ductility of the tested specimens. Triantafillou (1996) investigated the effectiveness of strengthening masonry monuments with externally applied circumferential tendons to provide horizontal confinement or sheets epoxy bonded to the facades of masonry building serving the role of tensile reinforcement. This technique was proved to be an efficient and effective solution for strengthening if aesthetics or other consideration is of no importance. Hartley et al. (1996) examined the performance of repaired concrete block walls damaged by ground subsidence. The original walls were subjected to simulated foundation settlement to observe cracking due to in-plane loading and then the damaged walls were repaired using carbon fiber tow sheet, epoxy-bonded to only one wall face. The test results indicated that a load carrying capacity of cracked wall increased about 80% of the original wall when repaired with carbon fiber tow sheets. Kuzik et al. (2003) investigated the out-of-plane flexural behavior of masonry walls reinforced externally with glass fiber reinforced polymer (GFRP) sheets and subjected to cyclic loading. The system, therefore, could be used to rehabilitate older masonry structures that are inadequately reinforced to withstand seismic events. Hamilton et al. (2001) conducted an experimental program in order to study the effectiveness of using FRP to strengthen unreinforced and under-reinforced masonry. They noticed that
the application of the GFRP composite provided a capacity approximately equivalent to a #5 (diameter = 16 mm) reinforcing bar spaced at 610 mm placed in the center of the wall. Therefore, most investigations have shown that for walls subjected to in-plane loads, the shear capacity of the walls was notably enhanced when strengthened with FRP sheets. Other investigations on the out-of-plane behavior of URM walls, strengthened with FRP sheets, have demonstrated that the flexural capacity of the strengthened walls can be dramatically increased (Ehsani et al. 1991; Hamilton et al. 1999; Valazquez et al. 2000). Krevaiaks and Triantafillou (2005) developed a computer aided methodology for strengthening of masonry walls using fiber-reinforced polymer strips. The proposed methodology is able to select the reinforcing pattern (positioning of the strips) and may also calculate required cross sectional areas of FRP. Elgawady et al. (2006) and Elgawady et al. (2007) investigated the behavior of FRP strengthened masonry wall specimens under constant gravity load and incrementally increasing in-plane loading cycles. The test results showed that FRP retrofitting significantly improved the lateral strength, stiffness, and energy dissipation of the test specimens.

A detailed review of literature shows that although some work is available on experimental investigation of unreinforced masonry walls against out-of-plane loading but work on FRP strengthened masonry walls are still limited especially under cyclic loading. Furthermore, simple analytical models that can predict out-of-plane load carrying capacity of FRP strengthened masonry walls are also not reported widely. Keeping these scopes in view, in the present study, suitability and effectiveness of fiber reinforced polymers (FRP) in strengthening unreinforced masonry walls against out-of-plane seismic/cyclic loading have been studied. For this purpose, two concrete masonry block wall specimens were cast. One specimen was used as control (un-strengthened) and other was strengthened with GFRP sheets. These wall specimens were then tested under out-of-plane loadings and load carrying capacities were obtained and compared. Results of experimental observations are presented in the form of load-displacement curves and response envelops. Simple analytical models, based on conventional assumptions of bending theory and force equilibrium conditions are also proposed to predict load carrying capacities and failure modes of control and FRP strengthened masonry walls.

EXPERIMENTAL PROGRAM

Test Specimens

The specimens subjected to out-of-plane unidirectional cyclic loading, were designed to be tested as one-way panels under 4-point bending. The two specimens had the dimensions of 1650 mm × 1450 mm × 200 mm (height, length and thickness). Concrete blocks with a cross section of 400 × 200 × 200 mm were used to fabricate the masonry walls for out-of-plane loading. The strengthened specimen was strengthened by one layer of unidirectional E-glass/epoxy composite sheet added at the tension face and fully extended beyond the support points thereby covering the whole length of the test specimen. This reflects the practical application of FRP strengthening of exterior masonry infill walls in existing buildings to withstand out-of-plane loading caused by seismic forces. The FRP material is assumed as E-glass/epoxy system with the following properties: number of layers = 1; thickness of layer, \( t_f = 1.0 \text{ mm} \); tensile modulus, \( E_f = 30000 \text{ MPa} \); tensile strength, \( f_{fu} = 540 \text{ MPa} \).

Test Setup

As mentioned before, the wall specimens were laid horizontally and then tested as one-way slabs under 4-point bending as illustrated in Figure 1. The control wall specimen was subjected to monotonic increasing static load while strengthened wall specimen was subjected to unidirectional vertical cyclic loading (i.e. half cyclic loading). For control specimen, cyclic load was not applied due to its very small expected out-of-plane strength. Figure 1 shows the picture of designed experimental setup for out-of-plane loadings.

Figure 1. Test setup under out-of-plane loading.
DISCUSSION OF TEST RESULTS

The load versus the vertical deflection relationships for control and strengthened specimens subjected to out-of-plane loading are separately shown in Figs. 2 and 3. For control wall there is a continuous increases in the deformation with the load, however, for strengthened specimen load-displacement curve is in the form of hysteric loops. This is due to the fact that for control specimen a continuous increasing quasi-static type of load was applied whereas for strengthened specimen load was quasi-static but unidirectional cyclic. The increment in the load was maintained about 1.0 kN in every next cycle. As mentioned before, for control specimen cyclic load was not applied due to its very small out-of-plane strength.

Figure 2. Load-displacement variation for control specimen.

Figure 3. Load-displacement variation for strengthened specimen.

To illustrate the advantages of using composite sheet as strengthening material a load-deformation envelop of strengthened specimen and load-deformation curve of control specimen are presented together in Fig. 4. The failure load of the strengthened specimen was 166.7 KN compared to 17 KN for the control one (about 900% gain in strength). This dramatic increase in the load carrying capacity of strengthened wall clearly shows great benefits of the composite sheet in transferring the masonry wall from individual concrete blocks to a one unit masonry wall that is capable of carrying high flexural stresses. Figure 4 further shows that the deformation capacity of the strengthened wall was increased dramatically after strengthening with GFRP sheet in the tension side of the wall.

Figure 4. Load-displacement envelopes for wall specimens.
ANALYSIS AND PREDICTIONS

The load carrying capacities and failure modes of control and strengthened wall specimens were analyzed using the beam theory with conventional assumption of plane section before bending remains plane after bending. Steps of the analysis can be summarized for control and strengthened specimens as mention under the following sections.

Control Specimen

The first step in the analysis of control specimen is to transform the actual block into an equivalent section. The un-strengthened control specimen is expected to fail once the masonry in the tension side cracks. The major steps for the analysis can be summarized as:

1. Determine the equivalent thickness of the masonry block \( t_{eq} \) from

\[
\frac{121}{B} \sqrt{I_g(\text{actual})} = t_{eq}
\]

where, \( B_b = \) block width; and \( I_g(\text{actual}) = \) gross inertia of actual block section.

2. Get the moment capacity \( M_{max} \) of the wall section from

\[
M_{max} = \frac{b_w t_{eq}^2 f_m'}{6}
\]

where, \( b_w = \) wall width; and \( f_m' = \) tensile strength of masonry wall, taken as 0.1 \( f_m' \); where \( f_m' \) represents crushing strength of the masonry.

3. Get the load carrying capacity of control wall from

\[
P_{max} = \frac{2M_{max}}{a}
\]

where, \( a \) is the shear span of the wall specimen.

Strengthened Specimen

The strengthened specimen may fail either in flexure (due to masonry crushing or FRP fracture) or shear (due to failure of the masonry units). The load carrying capacities against these two modes of failure can be obtained as detailed under the following sections.

Load carrying capacity against flexure

In order to compute load carrying capacity of FRP strengthened specimen against flexure, stress-strain distribution across the section of FRP-strengthened specimen is needed. The said distribution is shown in Figure 5. The major steps for the analysis can then be summarized in the following.

1. Compute neutral axis depth using following equation.

\[
e = -\frac{B + \sqrt{B^2 - 4AC}}{2A}
\]

Above equation is derived from the equilibrium of internal forces across the cross section of the wall (Fig. 5). In this equation,

\[
A = 0.85 f_m' \beta_1 ;
\]

\[
B = e_{\mu} E_f t_f = 0.003 E_f t_f ;\text{ and}
\]

\[
C = -e_{\mu} E_f t_f h = -0.003 E_f t_f \left( t_{eq} + \frac{t_f}{2} \right)
\]

Here \( E_f \) represents tensile modulus of FRP material; and \( t_f \) denotes its thickness (i.e. thickness of FRP).
2. Compute the tensile strain in the FRP using

\[
\varepsilon_f = \varepsilon_{\text{max}} \left( \frac{h}{c} - 1 \right) = 0.003 \left( \frac{h}{c} - 1 \right) = 0.003 \left( \frac{t_{\text{eq}} + \frac{t_f}{2}}{c} - 1 \right)
\]  

(8)

Above equation is derived from similar triangles of strain diagram as shown in Fig. 5. It is to be noted that the FRP strain should be less than the fracture strain for compression failure to occur.

3. Calculate the moment capacity of the wall section from

\[
M_{\text{max}} = 0.85 f_m' \beta f c b_w \left( h - \frac{\beta c}{2} \right)
\]

(9)

4. Compute the load carrying capacity of the strengthened wall at flexural failure using

\[
P_{\text{max, flexure}} = \frac{2M_{\text{max}}}{a}
\]

where, \( a \) denotes shear span of the wall specimen.

Load carrying capacity against shear

According to the ACI (1997) the shear strength of the masonry wall (in MPa) can be calculated from

\[
f_{\text{svm}} = \min \{ 0.125 \sqrt{f_m'} , 0.83 \nu + 0.45 N_v / A_v \}
\]

(11)

where, \( \nu = 0.26 \) MPa or 0.41 MPa, depending on the type of masonry; \( N_v \) = axial load in Newton; and \( A_v \) = area in mm².

Having known the shear strength of the masonry, the maximum load carrying capacity of the wall against shear failure can be estimated by the following simple equation.

\[
P_{\text{max, shear}} = 2f_{\text{svm}} t_{\text{eq}} b_w
\]

(12)

The actual out-of-plane load carrying capacity of the strengthened wall specimen shall be taken as the least of that given by flexural strength equation (i.e. Eqn. 10) and shear strength equation (i.e. Eqn. 12).

Table 1. Prediction of failure loads and modes of failure for wall specimens

<table>
<thead>
<tr>
<th>Wall Specimen</th>
<th>Load capacity</th>
<th>Mode of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical</td>
<td>Experimental</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Against flexure</td>
<td>Against shear</td>
</tr>
<tr>
<td>Strengthened</td>
<td>185.7 KN</td>
<td>169.17 KN</td>
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</tbody>
</table>
COMPARISON OF ANALYTICAL PREDICTION WITH EXPERIMENTAL RESULTS

Table 1 shows a comparison between analytically predicted and experimentally obtained load carrying capacity and failure modes of wall specimens. Since for control specimen it was expected with confidence that failure will be directed to flexure only, flexural load carrying capacity is only predicted. The prediction is in close agreement with experimentally obtained value. For strengthened wall, however, load carrying capacities are predicted against flexure and shear both and prediction is found to be smaller against shear (169.17 kN). Therefore, it is expected that the failure should be directed by shear and not by flexure. The experimentally observed load carrying capacity of strengthened specimen provides the load value as 166.7 kN and indicates the failure type as shear failure. The predicted value and nature of failure both are in good agreement with this experimental observation.

CONCLUSIONS

The behavior of control and FRP strengthened unreinforced masonry walls against out-of-plane seismic loading was experimentally and analytically investigated. The results of tested specimens showed that the FRP makes the wall to work as one unit and increases its strength and deformation capacity dramatically. For specimen of present study, it was observed that use of FRP sheets increases the flexural and shear capacities manifold (up to 900%) with respect to un-strengthened (control) specimen. These results thus show the great potential of externally bonded FRP sheets in upgrading and strengthening (rehabilitation) of masonry walls against out-of-plane seismic loads. The load carrying capacity and failure modes of control and FRP strengthened masonry walls were also predicted using simple analytical models and excellent agreements were observed with test results. The results indicated that the proposed simple models are capable of predicting load carrying capacities and failure modes of strengthened and un-strengthened walls satisfactorily.

REFERENCES


