In-plane shear strength of masonry wall strengthening by two distinct FRPs

Ataur Rahman† and Tamon Ueda*

†M. of Eng., JSPS RONPAKU Fellow, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628
*Dr. of Eng., Professor, Faculty of Engineering, Hokkaido University, Sapporo 060-8628

This paper experimentally investigates the performance of externally strengthened masonry walls under in-plane loading using two types of fiber reinforced polymer (FRP) sheets, they are: synthetic FRPs; Carbon, PET and Nylon-FRP, and FRPs with natural fibers; Jute and Cotton fibers. Conventional FRPs possess superior mechanical strength than natural FRPs, but they are expensive and have poor recycling and non-biodegradable properties. The experimental results demonstrate that a significant increase in the in-plane shear capacity of masonry can be achieved after strengthening, but ductility is compromised when CFRP is used. At the end, a simplified model for evaluating shear strength of FRP retrofitted masonry wall is proposed and validated with the experimental results.

Keywords: masonry, FRP strengthening, low cost bio-fiber, shear strength modeling.

1. INTRODUCTION

Very recent earthquakes in Nepal have caused an extensive damage in a large number of old masonry buildings. Many of them were designed as unreinforced or poorly reinforced masonry structures, based on empirical equations with little or no consideration of lateral loads. Careful observation into those structures reveals that damage was mainly due to the in-plane shear failure and the out-of-plane bending or slip during the tremor of a 7.9 magnitude earthquake. Therefore, there is an urgent need to improve the performance of unreinforced masonry (URM) structures by retrofitting and strengthening them to resist potential earthquake damage.

Seismic performance of these structures is largely dependent on the strength and behavior of in-plane shear walls. The behavior of masonry walls under in-plane loads can generally be divided into two categories, shear and flexural. Whether a wall is dominated by shear behavior or flexural behavior is largely dependent on the aspect ratio \(L/H\) and vertical compression on the masonry \((\sigma_v)\). For slender walls \(L/H\) less than 1.0 with relatively light axial stress, behavior is usually dominated by flexure and the strength is limited by either rocking or
toe-crushing preceded by a flexural cracking. For stocky walls \(L/H\) greater than 1.5 with moderate to heavy axial stress, shear usually dominates through bed joint sliding or diagonal tension cracking\(^1\)\(^2\). Among these four inelastic failure modes (see Fig. 1), rocking and sliding shear are classified as deformation controlled phenomena because large lateral deformation of walls and piers is possible without a significant loss in strength. In contrast, diagonal tension and toe crushing behavior modes are known as force controlled phenomena because the ultimate failure can be abrupt with little or no subsequent deformation. Stair-stepped diagonal cracking can also be considered as a deformation controlled action because frictional forces along bed joints are conserved with vertical compressive forces. However, diagonal tension cracking must be classified as a force-controlled action unless stair-stepped cracking can be distinguished from diagonal cracking through units\(^3\). It should be noted that not all these failure modes will involve collapsing of the masonry shear wall, and the final failure may be a combination of several failure modes.

FEMA 356\(^3\) provides most up-to-date guideline for analysis of masonry considering performance-based design. Three performance levels are defined and used as discrete points to guide a rehabilitation design based on the expected performance of a building. Performance levels are based on the amount of damage to both the structural and non-structural elements. The three defined levels for primary structural elements are
Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The guideline states two procedures for determining the acceptability of URM walls as a function of these performance levels. They are Linear Static Procedure (LSP) and Nonlinear Static Procedure (NSP). For any of the procedures, a load-deformation backbone curve required to determine the strength and expected level of performance of the component. Detail description of these procedures can be found in Chapter 3 and 7 of FEM A 356. However, design guidelines based on component performance for FRP retrofitted masonry walls are still lagging and this study aims to spotlight on this backdrop to some extent.

Various techniques e.g., ferrocement, shotcreting overlay, grout injection, FRP external bonding, posttioning with external cable, etc. are available and getting popular for retrofitting of existing masonry structures. The benefit of using FRPs as potential strengthening material comes from the reduction in handling costs; despite additional material costs, and they are easy to install due to light weight.

There is enough potential for agro-based product as an additives/reinforcement materials. Natural fibers offer many technical and ecological benefits for their use in reinforcing composites. In addition to that natural fibers are biodegradable or recyclable depending on the selected matrix. Many types of natural fibers have been investigated for use in plastics including cotton, jute, kenaf, sisal, coir, flax etc. These materials are predominantly used as a replacement for conventional synthetic and petroleum-based fibers. Though the strength of bio-fibers is not as great as conventional fibers, the specific properties are comparable and they are compatible with conventional resins.

The aim of seismic retrofitting is to upgrade the ultimate strength/deformation of the structure by improving the structure’s ability to undergo inelastic deformation without fully collapsing during an earthquake. When FRPs are bonded to the surface of the walls, diagonal tension failure or compressive crushing failure at wall toe is quite common. Also, premature debonding or fracture of FRP was commonly observed during the test and, in general, FRP could not reach its ultimate strength.

Experimental tests indicate that the failure patterns are affected by the strength, orientation, amount and anchorage length of FRP. In general, the possible failure mode for masonry strengthened with FRP can be a combination of several mechanisms such as, excessive cracking due to tensile stresses in the wall, crushing of masonry in the compression zone, shear-slip of masonry, FRP debonding, and FRP rupture.

In this study, CFRP have been used as conventional but expensive strengthening materials. On the other hand PET-FRP, Nylon-FRP, Jute-FRP and Cotton-FRP have been used as low cost strengthening materials. A comparison of these FRPs in terms of strength and deformation has been shown in this study. The strength of CFRP is higher than PET-FRP, whereas PET-FRP possesses a relatively higher fracturing strain than CFRP (see Fig. 2), which is an essential property of a strengthening material to be coherent with the brittle nature of masonry. On the contrary, natural fibers like Jute and Cotton are much weaker than these two, but are quite available at low cost and have significant elongation at failure. Similarly, Nylon-FRP has also a good ductile behavior. The purpose of this study is to show the difference in behavior of masonry shear wall strengthening with these distinct FRPs and the superiority of the one type of FRP over the others. Ultimate load-bearing capacity, deformation at peak load, and mode of failure, are observed in this study for two different arrangements of the FRPs on the surface of the wall. At the end, a simplified model based on effective strain in FRP, for calculating in-plane shear strength of masonry wall is proposed.
2. EXPERIMENTAL PROGRAM

A total of 11 masonry walls were investigated for the study. The nominal dimensions of these walls were 1270 \( \times \) 1020 \( \times \) 120 mm. Table 1 gives the details of the walls. In this table, RW stands for Reference Wall, P for PET-FRP, C for CFRP, JT for Jute-FRP, CT for Cotton-FRP, N for Nylon-FRP, D for Diagonal strip configuration, F for Fully wrapped wall and S for Solid bricks.

FRP sheets were applied in a single ply using a wet layup procedure on wall specimens in two different configurations as shown in Fig. 3. For fully wrapped walls (Fig. 3b), FRPs that have unidirectional fibers (CFRP and PET) were applied in horizontal and vertical wraps according to Fig. 4. FRPs with bidirectional fibers (Cotton and Jute) were applied in a single ply (only horizontal wrap). Epoxy resin having the properties indicated in Table 2 was applied over the wall and FRP sheet wherever necessary. A pre-compression of 40 kN which is equivalent to uniform pressure of 0.25 MPa, was applied on the top of the wall through two hydraulic jacks, prior to incrementally increasing shear loading as shown in Fig. 5. These two vertical loads restricted the rotation of the top beam only to some extent, as the beam was not restrained against rotation during the evolution of lateral load. A detail description of the experimental procedure can be found in the paper by Rahman and Ueda^{14}.

The mechanical properties of Jute, Cotton and Nylon mentioned in Table 2 were evaluated following the ASTM^{15,16,17} standard testing procedures. For each case, three samples were tested and the average results of these three are posted in Table 2.

3. EXPERIMENTAL OBSERVATION

3.1 Behavior of Reference Walls URM (RWS1, RWS2)

These two walls were tested as reference wall to make a comparison with rest of the strengthening walls mentioned in Table 1. The wall RWS1 failed in flexure followed by a shear slip where as wall RWS2 failed in flexure followed by toe crushing as shown in Fig. 6. The difference in failure modes for the reference specimens RWS1 and RWS2 can be attributed to the location where the first flexural cracks appeared in these two specimens and their way of propagation. In RWS1, first flexural crack appeared at the very bottom of the wall and propagated horizontally in a straight fashion towards the wall toe, which facilitated the wall to slip along the crack path. Once a crack forms at the wall heel, no tension force perpendicular to it can be transmitted across it, and the load drops by a little. As long as the crack is narrow, however, the wall can still transmit some shear forces in its own plane through friction of the surface roughness that can be characterized as elasto-plastic behavior. With further deformation and slip, the interlocking planes suffer from substantial damage and are flattened to some extent after which the wall reaches in a state of kinematic equilibrium where only some residual frictional shear resistance prevails^{18}, and remains even with the applied displacement as can be seen in Fig

Table 1 FRP configurations and test results for masonry specimens

<table>
<thead>
<tr>
<th>Wall ID</th>
<th>Peak Load (kN)</th>
<th>Def. at Peak Load (mm)</th>
<th>FRP configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWS1</td>
<td>48</td>
<td>8.7</td>
<td>Reference wall</td>
</tr>
<tr>
<td>RWS2</td>
<td>30</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>PSD1</td>
<td>114</td>
<td>8.9</td>
<td>PET diagonal</td>
</tr>
<tr>
<td>PSD2</td>
<td>101</td>
<td>24.7</td>
<td></td>
</tr>
<tr>
<td>PSF</td>
<td>168</td>
<td>6.5</td>
<td>PET fully wrap</td>
</tr>
<tr>
<td>NSD</td>
<td>103</td>
<td>15.5</td>
<td>Nylon diagonal</td>
</tr>
<tr>
<td>CSD1</td>
<td>95</td>
<td>2.9</td>
<td>Carbon diagonal</td>
</tr>
<tr>
<td>CSD2</td>
<td>94</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>CSF</td>
<td>107</td>
<td>2.7</td>
<td>Carbon fully wrap</td>
</tr>
<tr>
<td>JTSF</td>
<td>104</td>
<td>21.4</td>
<td>Jute fully wrap</td>
</tr>
<tr>
<td>CTSF</td>
<td>133</td>
<td>15.7</td>
<td>Cotton fully wrap</td>
</tr>
</tbody>
</table>

Fig. 3 Wrapping technique of masonry wall with FRP, (a) FRP diagonal bracing (b) Fully wrapped with FRP

Fig. 4 Specimen preparation
7. In reference wall RWS2 first flexural crack appeared at some distance from the bottom on the wall heel side and propagated towards the wall toe in a stepped fashion (see Fig. 6). This failure pattern prompted a rocking phenomenon in the wall instead of shear sliding and consequently a softening behavior was observed in the post-peak regime (see Fig. 7) caused by a toe crushing in the wall. It is worth noting here that the location where the first flexural crack will appear is somehow difficult to predict as was the case for these two reference walls. This is largely because of the non-homogeneous nature of masonry wall fabrication that creates several planes of weakness along the horizontal joints between masonry bricks.

So, it can be said that an earlier flexural crack normally followed by either a toe crushing or a sliding shear type of failure. Many researchers\(^9\) observed similar failure mode in masonry walls. Moreover, it is quite evident in Fig. 7 that the shear strength for masonry sliding is higher than that of rocking and toe crushing because shear sliding endures a resistance along the entire crack plane where as toe crushing occurs due to accumulation of compression stress on a very small area at the crack tip on the wall toe.

3.2 Behavior of FRP Reinforced Walls

(1) Diagonally braced walls

These walls are strengthened with FRP diagonal strips according to Fig. 3a. For the case of Nylon-FRP diagonal strips (NSD), at a load of 62 kN a fine line crack developed at wall heel and propagated all the way to the wall toe with further loading. When the load reached to 100 kN, sound of debonding of the diagonal tension strips on both sides of the wall was heard and the load dropped by a little. Almost simultaneously a crack developed at the wall top on the load end and travelled downward in a stepped fashion as shown in Fig. 8. With further

<table>
<thead>
<tr>
<th>Properties</th>
<th>FRP materials</th>
<th>Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>PET (600)</td>
<td>CARBON (FIS-C1-20)</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>10</td>
<td>245</td>
</tr>
<tr>
<td>Elongation at fracture (%)</td>
<td>10±1</td>
<td>1.5</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.841</td>
<td>0.111</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>300</td>
<td>250</td>
</tr>
</tbody>
</table>

Fig. 5 Schematic diagram of experimental setup of shear wall

Table 2 Properties of fibers and adhesive

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displacement, load did not increase much but the crack opening only widened and at that point the specimen was unloaded. For the case of walls diagonally braced with CFRP strips, one wall showed (CSD1) flexural cracking and the other one had a crack pattern similar to NSD but endured a rupture of the FRP tension diagonals as can be seen in Fig. 9.

On the other hand, walls reinforced with diagonal PET-FRP strips (PSD1 and PSD2), identical crack patterns, similar to CSD2, were seen followed by some toe crushing (see Fig. 10). The peak load of 114 kN and 101 kN respectively did not attenuate much with the applied displacement for quite a long time, and at that stage the experiment was ceased.

(2) Walls fully wrapped with FRPs

These walls were strengthened by fully wrapping with FRP sheets according to Fig. 3b. Jute and Cotton sheets, both having bi-directional fibers, were applied on the wall in a single ply. For wall strengthened by Jute-FRP, no significant crack or damage over the Jute-FRP was noticed throughout the loading history but a ductile deformation can be observed (see Fig. 11). The initial stiffness was similar to URM and a softening tendency can be seen after the load reached to 50 kN. The load was increasing steadily to 100 kN and a crack was observed in the wall heel side and the crack opening only widened with the applied displacement. Subsequently the wall bottom on the heel side started to come out of the anchorage gird, and the experiment was ceased at that stage. On the other hand wall (CTSF) reinforced with Cotton-FRP, also showed quite ductile load-deformation behavior. This wall also failed at a peak load of 133 kN in anchorage grip similar to JTSF. Since these walls were fully wrapped by the FRP sheets, damage, if any, could hardly be detected by visual observation.

In contrast, wall CSF and PSF both have the premature anchorage failure similar to CTSF and JTSF, but wall wrapped with PET-FRP shows better ductility than CFRP wrapping. It is due to the fact that higher the percent of CFRP, higher will be the stiffness as well as shear strength of masonry wall. However, higher amount of CFRP material do compromise with the ductility of the wall and are not fitting well with the purpose of seismic strengthening.
3.3 Load-Deformation Response

The load-deformation responses of strengthened masonry walls are plotted in Fig. 12 and Fig. 13. Fig. 12 depicts the load-deformation response of diagonally braced masonry walls. It is quite evident from the figure that, the lateral load capacity increased more than twice for all of the retrofitting walls. The lateral load increase quite linearly until a potential crack appeared in those walls. One important characteristic here is that the wall diagonally braced with CFRP strips, shows a brittle type of failure where load reduction was quite abrupt with no softening at all. This was due to the crushing at wall toe immediately followed by a rupture of the tensile CFRP strips on the both side of the wall (Fig. 9). In contrast, walls strengthened by either PET-FRP or Nylon-FRP, show quite ductile nature of inelastic behavior, followed by a gradual softening regime, retaining some residual strength. The development of diagonal strain at the center of these two walls can be seen in Fig. 14. It is interesting to note that until the initiation of a potential diagonal cracking (Fig. 8 and Fig. 10) the development of strain in the diagonals strips are quite low. After the onset of cracks, the internal stresses transfer from masonry to FRP, and the internal strain in FRP rises quite significantly but remains less than its fracturing strain.

On the other hand, Fig. 13 demonstrates the load-deformation response of the walls fully wrapped by FRPs. The shear capacity of those walls increased by more than three time of that of unreinforced walls. The deformation does not depict the real picture as it was stated that the walls underwent some rotation at their bottom and a premature failure at the grip was noticed. Even then, the deformability of those walls can be foreseen from these load-deformation plots. Wall retrofitted by bio-FRP such as Jute-FRP and Cotton-FRP behave in a ductile manner than their counterpart CFRP wall. PET-FRP wall can resist more lateral load than any of them, where as the lateral shear resistance by Cotton-FRP wall is more than Jute-FRP wall.

4. ANALYTICAL MODEL

Until now, very limited number of design models have been developed and adopted in standards for masonry wall retrofitted with externally bonded FRP (19,20). All of them have the common terminology and based on the assumption that the shear strength of masonry wall is sum of the contribution from uncracked masonry wall and contribution from FRP. Thus, the total shear force is given by,

$$V_T = V_M + V_{FRP}$$

(1)

The first term, $V_M$, may be calculated according to provisions in FEMA 356 (18), which gives the following four different equations to calculate the shear strength of URM for four modes of failure (Fig. 1), they are:

1) Shear strength for rocking:
\[ V_M = V_{rock} = 0.9 \alpha_e \sigma_y A_e \left( \frac{L}{H} \right) \]  
\[ V_M = V_w = A_g \sigma_y A_e \left( \frac{L}{H} \right) \left( 1 - \frac{\sigma_y}{0.7 f_{mc}} \right) \]

3) Shear strength for bed-joint sliding:
\[ V_M = V_{slid} = A_g \sigma_y A_e \left( \frac{L}{H} \right) c (\sigma_y \tan \phi) \]

4) Shear strength for diagonal tension cracking:
\[ V_M = V_{dt} = f_{dt} A_g \left( \frac{L}{H} \right) \left( 1 + \frac{\sigma_y}{f_{dt}} \right) \]

Some of the parameters used in these equations depend on test results. In absence of candid test results for masonry compressive strength, cohesion and masonry diagonal tension strength, Eq. (6)\(^2\), Eq. (7)\(^2\) and Eq. (8)\(^2\) can safely be used for a conservative value of these three parameters.

Where,
\[ f_{mc} = 0.55 \left( f_h \right)^{0.7} \left( f_m \right)^{0.3} \] 
\[ c = 0.0337 \left( f_m \right)^{0.6} \] 
\[ f_{dt} = 0.075 \left( f_{mc} \right)^{0.375} \]

Here, \( V_M \) = shear strength of URM wall; \( L, H, b \) = length, height and thickness of the masonry wall; \( f_{mc} \) = compressive strength of masonry prism; \( A_e \) = sectional area of wall = \((L \times b)\); \( \alpha_1 \) = factor for boundary condition (0.5 for cantilever wall and 1.0 for fixed-fixed wall); \( \tau_{slid} \) = average bed-joint sliding shear stress of URM wall; \( c \) = cohesion between mortar and brick; \( \sigma_y \) = vertical compression on masonry wall; \( \phi \) = frictional angle at sliding surface; \( f_d \) = masonry diagonal tension strength; \( f_{dt} \) = uniaxial compressive strength of brick and mortar respectively.

So, the major differences between available models are attributed to FRP contribution \( V_{FRP} \) and how the mechanism of this contribution has been clarified. The strength of \( V_{FRP} \) will be affected by but not limited to the strength of FRP, the orientation of FRP, the anchorage length of FRP, the modulus of elasticity of FRP, and more importantly, the strain distribution in FRP. Therefore, many authors\(^{12, 15}\) argued that it is impossible to accurately predict the FRP contribution to shear strength. It would be ideal if FRP reaches its tensile strength at failure. However, most experimental data showed that the contribution of the FRP to the shear strength of masonry wall is far less than its ultimate tensile strength due to premature debonding.

In this section, an attempt is made to propose a simplified analytical model based on effective strain, which can predict the FRP contribution in masonry wall fully wrapped and diagonally braced with any type of FRP, with fair accuracy.

4.1 Effective Strain Based Model

The proposed model is based on the assumption that the effective tensile strain in FRP varies parabolically along the principal compression diagonal having maximum strain at the center in a manner similar to the distribution of internal shear stress along the length of the wall as shown in Fig. 15. The length of compression diagonal \( D \) (Eq. 9) is subdivided into a finite number of strips \( m \) of equal width \( w_s \) which can be taken conveniently as the diagonal length of a half brick \((D/2)\) plus its surrounding mortar thickness \((t_m)\) (Eq. 10). Here, \( h \) is the height of a single unit and \( l \) is the length.

\[ D = \sqrt{H^2 + L^2} \]  
\[ w_s = \sqrt{(h + t_m)^2 + \left( \frac{l}{2} + t_m \right)^2} \]

So, the number of strips is, \( m = \frac{D}{w_s} \)

It is further assumed that before formation of any potential diagonal cracking in brick masonry, the effective strain in FRP is quite low, as shown in Fig. 14. The diagonal tension crack, once formed, spreads either immediately or at only higher load, traversing along the compression diagonal of the wall in a stepped fashion through mortar between bricks. Crack may go through the bricks also, depending on the relative strength of brick and mortar. Once a crack is formed, no tension force perpendicular to the crack can be transmitted across it. However, FRP wrap, more specifically the vertical wrap (or the vertical component of the bi-directional sheet), whose chief contribution is in flexure, adds some stiffness to the wall and as a result it retards the formation of diagonal tension crack and constrains the crack opening. As long as the crack is narrow, it can still transmit some shear forces in its own plane through friction of the surface...
roughness. This sizable contribution to shear force has to be incorporated with an addition term \( V_{ad} \) (Eq. 11) in Eq. (2) to Eq. (5), depending on the governing failure mode of FRP retrofitted wall that limits the shear strength. Eq. (11) gives an empirical relationship among the parameters used in this equation.

\[
V_{ad} = K \frac{\rho_f E_f L}{H}
\]  
(11)

Where, \( \rho_f = \frac{n t_f}{b} \) = FRP area fraction in horizontal direction, 
\( n \) = number of FRP ply, \( t_f \) = FRP thickness, \( E_f \) = FRP elastic modulus. The concept of Eq. (11) has been derived from the idea of contribution of bricks, such as bricks in compression zone and aggregate interlocking along crack plane, similar to the calculation of total shear of a RC beam, where it is assumed that there is a sizable contribution of the compression zone and aggregate interlocking force to the total shear resistance. It is further assumed that this contribution starts to take place on the onset of diagonal flexural-shear cracking. Eq. (11) was derived based on similar principle, where it is assumed that the amount of FRP and its stiffness as well as the aspect ratio \((L/H)\) of the wall will have some influence on the contribution of bricks. The empirical constant \( K \) in this equation was found to be 25 in SI unit. More test results for different aspect ratios of the wall and for different FRP ratios are needed for a better correlation of this constant \( K \).

So, Eq. (1) which gives the total shear strength of FRP retrofitted masonry walls, takes the final shape as,

\[
V_T = V_M + V_{ad} + V_{FRP}
\]  
(12)

It is worth mentioning here that the proposed model can also predict the shear strength for other modes of failure as well. The effective strain for each strip can be calculated as,

\[
\varepsilon_i = \varepsilon_i \left( \frac{4d}{D^2} \right) (D - d_i)
\]  
(13)

Where, \( i = 1, 2, 3 \ldots \ldots \ m \) (m = number of strips)
In the above Eq. (13), the diagonal distance \( d_i \) from the center of the wall, can be calculated by Eq. (14),

\[
d_i = \frac{D}{2} - (i - 1) w_i
\]  
(14)

In this Eq. (13), \( \varepsilon_i \) is the maximum effective strain \( \varepsilon_{max} \), which can be calculated by the following Eq. (15), originally proposed by ACI 440.\textsuperscript{20}

\[
\varepsilon_i = \varepsilon_{ef}^{\prime} = 0.41 \frac{\sigma_{fm}}{nE_f t_f} \leq 0.9 \varepsilon_{fu}
\]  
(15)

The horizontal component of effective diagonal tensile strain found from Eq. (13) and Eq. (15) can be calculated as Eq. (16) by the rule of strain transformation (Mohr’s circle), where the effect of orthogonal strain along compression diagonal on this horizontal component \( \varepsilon_{ij} \) is insignificant and can be neglected for simplicity. Thus,

\[
\varepsilon_{ij} = \varepsilon_i \cos^2 \theta
\]  
(16)

where, \( \theta \) = angle between diagonal and base of the wall.
From Fig. 15, it is evident that the lateral shear contributed by the FRP is equal to the summation of all horizontal components of the diagonal tension developed in all of the diagonal strips. Thus,

\[
V_{FRP} = nE_f t_f w_i \sin \theta \left[ \varepsilon_{ij} + 2 \left( \varepsilon_{i2} + \ldots + \varepsilon_{ij} \right) \right]
\]  
(17)

The above Eq. (17) can be used for all types of FRP having fiber in horizontal direction. If the FRP fiber is oriented along the diagonal of the wall as for the case of wall strengthening with the diagonal bracings, the above Eq. (17) can be simplified as,

\[
V_{FRP} = n t_f E_f w_i \varepsilon_{max} \cos \theta
\]  
(18)

4.2 Model Implementation and Validation

In this proposed model the FRP contribution to lateral shear comes from the internal strains as explained in the model. The proposed model is best suited for the cases when the bonded FRP undergoes substantial debonding. Proposed effective strain based model will not be fitted well, when the FRP shows extensive fracture and damage. Table 3 gives a comparison between analytical prediction and experimental results of masonry shear strength for different FRP configurations. The information on in-plane tests on masonry wall retrofitted by fully wrapped FRPs are very limited and the uses of bio-FRP for masonry strengthening are yet to begin. The presented data in Table 3 depict that the proposed model can estimate the shear strength of FRP retrofitted masonry walls with reasonable accuracy where the average of the ratios of prediction to test results is 0.97 and the coefficient of variation is about 0.18. Only a few cases the prediction is poor, especially when the wall is reinforced with CFRP sheets. In the case of fully wrapped wall with CFRP sheet (CSF), the predicted shear strength was more than twice of the experimental observed value. This was due to the fact that the test panel did not reach its ultimate strength and failed prematurely in anchorage slip at grip of the wall bottom. Moreover, the model predicted higher effective strain than that was in experiment. Although anchorage slip was observed for other cases (PSF, JTSF, CTSF) also, but that happened at a later stage of the experiment when the wall reached at a constant state of load-deformation relationship as can be seen in Fig. 13. So, this proposed model can be implemented to almost all of the masonry walls that are reinforced with conventional FRPs and bio-FRPs having moderate to high fracturing strain.

In this proposed model, the failure mode of FRP retrofitted masonry can qualitatively be predicted from the aspect ratio of the walls. Having an aspect ratio less than one, the wall would presumably fail in flexural rocking followed by a toe crushing.
On the other hand, wall with an aspect ratio above one, can have an expected mode of failure similar to diagonal cracking. In both of the cases, debonding of FRP would take place rather than rupture.

5. CONCLUSIONS

In this experimental study, eleven masonry walls were tested, having been strengthened by two type of synthetic and comparatively expensive FRPs such as CFRP, PET-FRP, Nylon-FRP sheets and two types of naturally available and low cost FRPs such as Jute-FRP and Cotton-FRP, in two different configurations with similar boundary conditions. All the specimens were tested under constant vertical load and incrementally increasing in-plane loading. The rotation of the top beam was partially restrained by vertical loads applied at two points. Load-deflection characteristics were observed for each wall and subsequent damages were evaluated. Based on the foregoing results and observations, the following conclusions can be drawn:

1) This experimental study demonstrates the ability of all of the FRPs such as CFRP, PET-FRP, Nylon-FRP, Jute-FRP and

<table>
<thead>
<tr>
<th>Table 3 Verification of proposed model for FRP strengthened walls</th>
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<tr>
<td><strong>Retrofitting Type</strong></td>
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<tr>
<td>CA-FX-01</td>
</tr>
<tr>
<td>CA-FX-03</td>
</tr>
<tr>
<td>CSD</td>
</tr>
<tr>
<td>PSD</td>
</tr>
<tr>
<td>NSD</td>
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<tr>
<td>C1</td>
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<td>W2</td>
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<td>W3</td>
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<td>PSF</td>
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<td>JTSF</td>
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<td>CTSF</td>
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* DT-DB (or FR) = Diagonal tension in wall and debonding (or fracture) in FRP, SLD-DB (FR) = Sliding in wall and debonding (or fracture) in FRP, F-DB (FR) = Toe crushing in wall and debonding (or fracture) in FRP.
Cotton-FRP sheets to enhance the shear resistance to a great extent; more than twice the capacity of the URM wall in the case of diagonal bracing and about three times in the case of fully FRP wrapping. Among the fives, PET-FRP and Nylon-FRP have a better ductility performance than CFRP, as they show pronounced ductile behavior in pre-peak regime and softening behavior in post-peak regime. Ductility is a must needed criterion rather than strength for a structure to absorb substantial seismic energy and ensure structural integrity and margin of safety against collapse. Though the CFRP increases the shear capacity of a masonry wall, it substantially reduces the ductility of the wall, which may eventually cause an explosive type of masonry failure. On the other hand, Jute-FRP and Cotton-FRP also enhanced the shear capacity of masonry wall to almost thrice of that of URM walls, and they show better ductile behavior than CFRP or PET-FRP.

2) As masonry is quite fragile against lateral movement with a low lateral stiffness, diagonal bracing with PET-FRP sheet can be one of the options if the cost of the material is not compromised. If seeking for a low-cost strengthening material, Nylon-FRP, Jute-FRP and Cotton-FRP could be one of the variable alternatives, where not only capacity is enhanced but, at the same time, the wall is made quite ductile, reversing a catastrophic mode of failure to a ductile one. Moreover, unlike synthetic FRP such as CFRP, PET-FRP and Nylon-FRP, Jute and Cotton are bio-degradable materials, that do not pose any threat to the ambient environment.

6. RECOMMENDATIONS

Considering the aforementioned discussion, the following recommendation can be made:

1) In all strengthening work, cost of the material and installation is prime concern of both engineers and builders. The cross-diagonal bracing with PET-FRP requires least materials and minimum installation works, and whose material cost is less than CFRP. On the contrary, diagonal bracing with Nylon-FRP also showed good shear resistance and better ductility behavior than CFRP and PET-FRP and having lower cost than these two. Wall fully covered by CFRP or PET-FRP is not a suitable option for external strengthening due to the use of higher amount of materials that makes the wall much stiffer against lateral deformation, but they are quite good when Jute or Cotton sheet are used. However, structures will rarely be economic unless sensible decisions are made using whole-life costing and taking into account all the costs of repair and strengthening.

2) Proposed analytical model based on effective strain in FRPs, can fairly predict the shear strength of masonry wall retrofitted with different FRPs. The model shows a reasonable prediction of shear strength for masonry walls failed in debonding rather than fracturing in FRPs. For CFRP strengthened wall the model prediction is rather poor due to the estimation of higher strain value for CFRP. On the contrary, Jute and Cotton both have high fracturing strain and their effective strains are also high in transferring shear. The present work is not exhaustive and more test results on masonry retrofitted with bio-FRPs are necessary to validate the model for different strengthening schemes and for different anchorage types.

3) Bio-FRP composites made from natural fiber are renewable, cheap, completely or partially recyclable, and biodegradable. A lot of research needed to be done on bio-FRP, ranging from bond stress-slip model to resin-fiber interaction. A harmonized effort is necessary to bring the bio-FRPs in the vast strengthening market as lucrative retrofitting materials.

Research work, analytical modeling, model codes and provisions for RC structures strengthened by conventional FRPs such as CFRP and GFRP have gone a long way in the last two decades, whereas, it is still far away from standard design practice and performance based seismic assessment of masonry structures. A concerted effort and a harmonized approach are therefore necessary for masonry to meet that target. With the use of well-tested materials with reasonable cost, expert installation crews, and proper design guidelines, externally bonded FRPs made from natural fiber can be a unique solution to many masonry structures for retrofitting and rehabilitation purposes in the third world countries. Experimental results and recommendations proposed in this study can be one step forward in achieving this goal.

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