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SURFACE BOND CHARACTERISTICS OF FRP SHEETS FOR SEISMIC RETROFIT APPLICATIONS

B. Shadravan[1] and M. Saatcioglu[2]

ABSTRACT

Surface bond characteristics of carbon FRP sheets were investigated on concrete and masonry. A large number of rectangular prisms were tested under uniaxial tension, inducing direct bond stresses between surface bonded FRP and the substrate. Different test setups were used to simulate actual performance of FRP sheets in practice, including the test setup recommended by the Canadian Standard CSA S806-02. A parametric experimental investigation was conducted. The results provided much needed data to develop design information for surface-bonded FRP sheets as a seismic retrofit material for use in non-ductile reinforced concrete frames with masonry infill walls. The results were combined with those generated by others in assessing surface bond characteristics of FRP sheets. Relevant design information was developed and presented in the paper. It was found experimentally that effective bond length, which limits the tensile capacity of diagonal FRP tension elements, governs the strength of surface-bonded FRP. Furthermore, the effectiveness of FRP strips diminishes with increased strip width. These observations were incorporated in the design expressions proposed in the paper.

Introduction

The majority of non-ductile reinforced concrete frame buildings suffer damage during strong earthquakes. These buildings require seismic retrofits for improved performance. A large proportion of existing seismically deficient frames were built prior to the enactment of modern seismic codes. The majority includes concrete block or brick masonry infill walls. These structures often benefit from seismic retrofit strategies at the system level because of the presence of a large number of poorly designed non-ductile elements. This is usually achieved by drift control through lateral bracing. One of the attractive seismic retrofit techniques for such

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[1] Graduate Research Assistant, Dept. of Civil Engineering, University of Ottawa, Ottawa, Canada
[2] Professor and University Research Chair, Dept. of Civil Engineering, University of Ottawa, Ottawa, Canada

applications involves the use of surface bonded fibre-reinforced polymer (FRP) sheets. However, surface bond characteristics of FRP sheets under cyclic loading have not been fully understood. The FRP sheets exhibit brittle performance and often delaminate prematurely because of poor bond characteristics. The current research is aimed at developing design information for such applications with specific focus on bond length and ultimate load capacity.

Experimental Study

An experimental program was designed to investigate surface bond characteristics of FRP sheets on concrete and masonry substrates. The test program consisted of pull-out tests of 71 prisms with surface bonded carbon FRP sheets subjected to axial tension. This consisted of 58 concrete, 6 concrete block and 6 clay brick specimens. The test variables included; i) FRP bond length, ii) number of FRP layers, iii) width of FRP strips iv) substrate material (concrete, concrete block, and clay brick), v) loading (monotonically increasing static loading and cyclic loading), vi) concrete strength, and vii) test setup. The following sections provide a summary of test results on bond length and ultimate load capacity as affected by selected test variables.

The FRP sheets used were of Wabo-MBrace type, with carbon fibres. The tensile fibre strength was 4275 MPa and the elastic modulus was 228 GPa. The net thickness of sheets was 0.165 mm. The specimens were tested in the form of concrete prisms with a 150 mm square cross section. A U-shaped FRP strips were used, providing one FRP strip on each side as illustrated in Fig. 1. The FRP sheets were instrumented with strain gauges. The load was applied in direct tension gradually in deformation-controlled mode until failure.

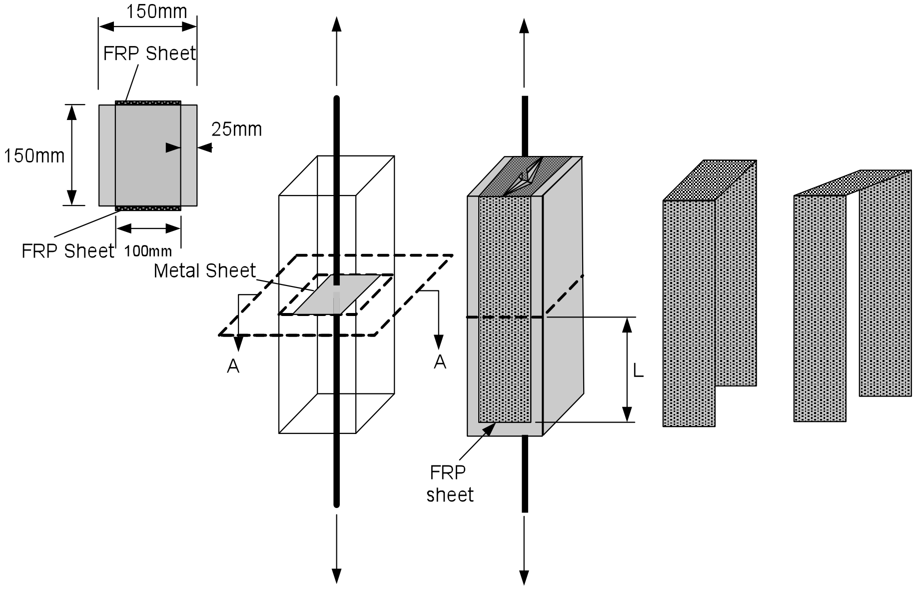
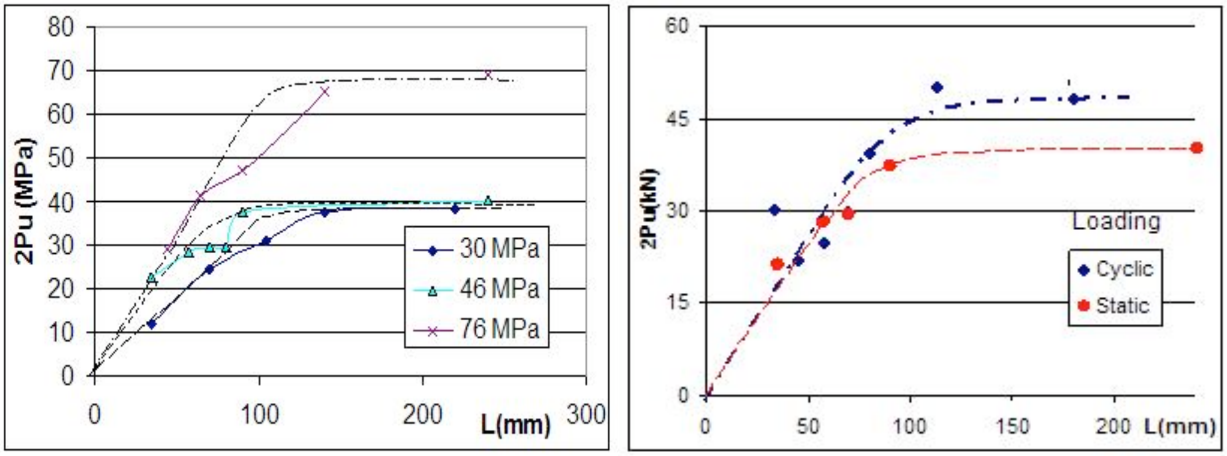


Figure 1. Typical test setup used in the experimental program

Test Results

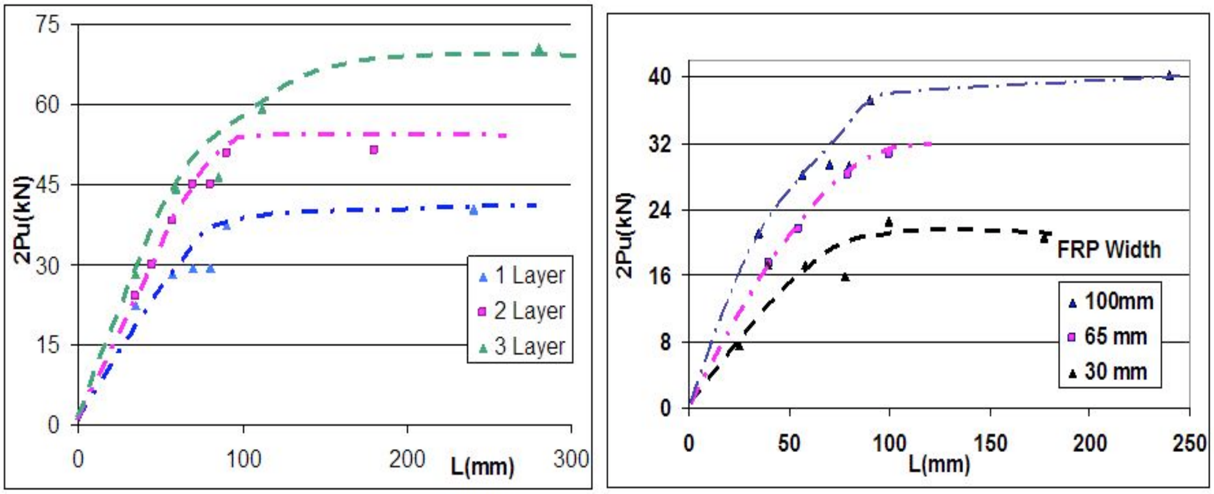
The tests demonstrated an effective bond length beyond which further increase in length could not improve the load capacity. This effective length, for the specimens tested in the current investigation, varied approximately between 90 mm and 120 mm depending on other test variables. Fig. 2 demonstrates the effects of test variables on ultimate load capacity and bond length. Each point plotted on the figure is the result of a different test specimen. The effective length corresponds to the point at which the curves show a significant rate of change in slope and become flat, indicating a little increase in capacity beyond this point with increased bond length. However, somewhat reduced brittleness was observed when bond length was increased.

The ultimate bond strength consistently improved with increasing concrete strength as shown in Fig. 2(a). This can be attributed to improved diagonal tension capacity of higher strength concretes, which resist higher forces before surface cracks lead to bond deterioration. The increase in ultimate load capacity showed approximately the same rate in all groups of specimens with different bond lengths. The limited test data that was generated indicate little or no influence of concrete strength on the effective bond length. Therefore, the effect of concrete strength on effective bond length may be neglected in design.



a) Effect of concrete strength

b) Effect of loading



c) Effect of number of layers

d) Effect of FRP strip width

Figure 2. The results of experimental parametric investigation on ultimate load and effective bond length

The significance of cyclic loading on effective bond length was assessed by comparing companion specimens under monotonic and cyclic loading (Shadravan and Saatcioglu 2009). This comparison is plotted in Fig. 2(b). The figure indicates improved bond strength under cyclic loading because of the more gradual failure observed during testing. It was observed that the ultimate load capacity as well as the effective length can be increased by approximately 20% due to cycling the load.

One of the test parameters investigated was the number of FRP layers. Higher number of layers resulted in higher ultimate load capacity, but the increase in capacity was not directly proportional to the number of layers. The effective length was also increased slightly with the number of FRP layers. This is illustrated in Fig. 2(c).

The width of FRP strip was another parameter that was investigated. It was observed that wider strips resulted in higher ultimate load capacity as illustrated in Fig. 2(d). However, the rate of increase in ultimate load capacity was not proportional to the increase in strip width. The effect of strip width on effective length was negligible.

Both concrete and brick masonry specimens suffered surface bond failures, whereas the concrete block specimens failed prematurely through the failure of the walls of block masonry units. The bricks showed similar behaviour to that for concrete specimens. Fig. 3 illustrates the ultimate strength versus bond length relationship for specimens with different substrates. The maximum normal stress, which was recorded in brick specimens, followed almost the same trend as that for concrete specimens. The higher bond strength of FRP on brick masonry is attributed to the narrower strip width used in these specimens.

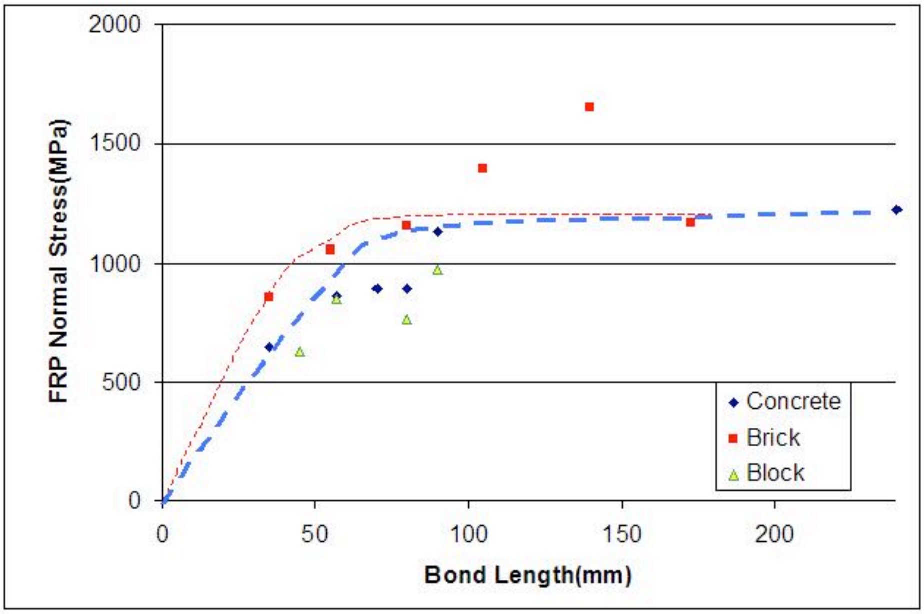


Figure 3. Strength of surface bonded FRP strips on different substrates

Development of Design Expressions

Design expressions were developed for ultimate load and effective FRP length. This was achieved through least squares fits on experimental data using power relationships. The number of FRP layers in these expressions was incorporated through FRP stiffness (nt_pE_p). This is valid when the same FRP material is used in each layer. Eq. 1 provides the expression for ultimate bond capacity of FRP sheets.

$$P_u = 4.25 \times c \times f'^{\,0.58}_c (n_p t_p E_p b_p)^{0.42}[1 - \exp(-0.02L_b)] \tag{1}$$

where; c = 1.0 for monotonic loading and 1.2 for cyclic loading. Concrete cylinder strength, f'_c is expressed in MPa. The number of layers, thickness, width and modulus of elasticity of FRP are denoted by n_p, t_p , b_p and E_p, respectively. The FRP bond length is denoted by L_b.

The predicted ultimate load capacities obtained by Eq. 1 are compared with experimental results of the current investigation in Fig. 4. Eq. 1 is also verified against 144 tests conducted by others (Bizindavyi and Neale 1999, Chajes et al. 1996, Maeda et al. 1997, Ren 2003, Tan 2002, Takeo et al. 1997, Ueda et al. 1999, Wu et al. 2001, Wu et al. 2002, Yuan et al. 2004, and Zhao et al. 2000), involving CFRP and GFRP strips. This is shown in Fig. 5. The results indicate good correlations of analytical and experimental results.

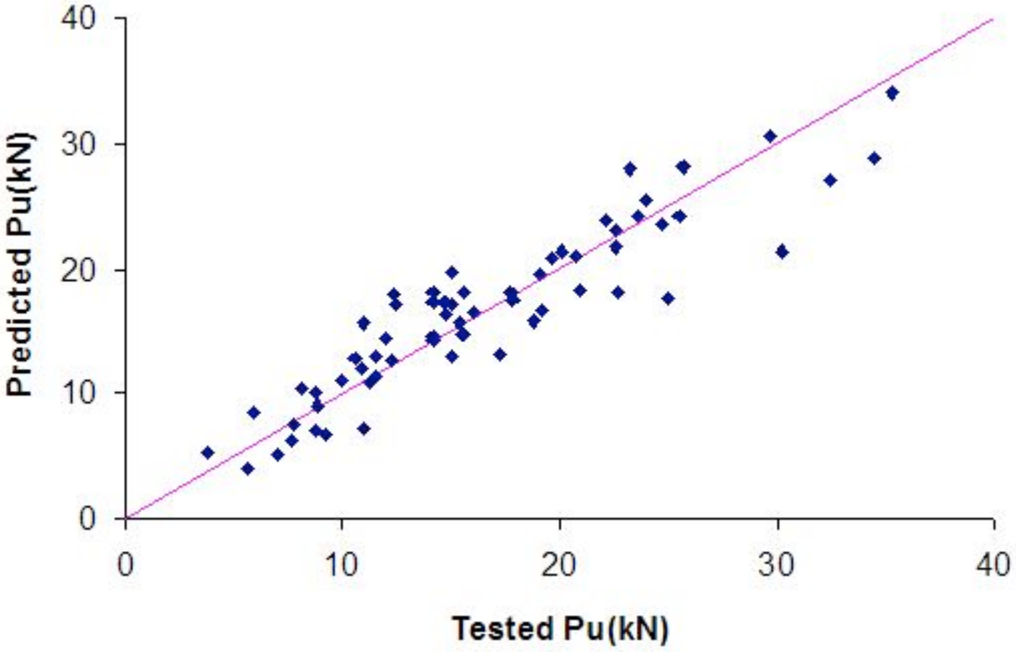


Figure 4. Correlation of results obtained by Eq. 1 with the results of current investigation

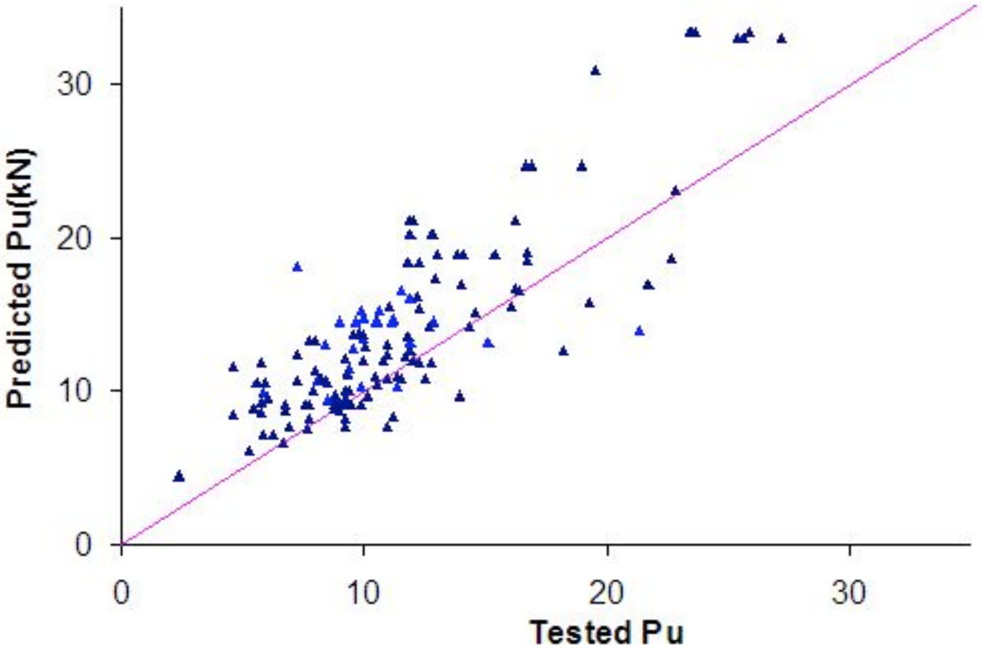


Figure 5. Correlation of results obtained by Eq. 1 with experimental data obtained by others

A design expression was also developed for effective bond length. The data shown in Figs. 2 and 3 were used for this purpose. Accordingly, Eq. 2 can be used to estimate the effective length of FRP when the failure is governed by bond failure.

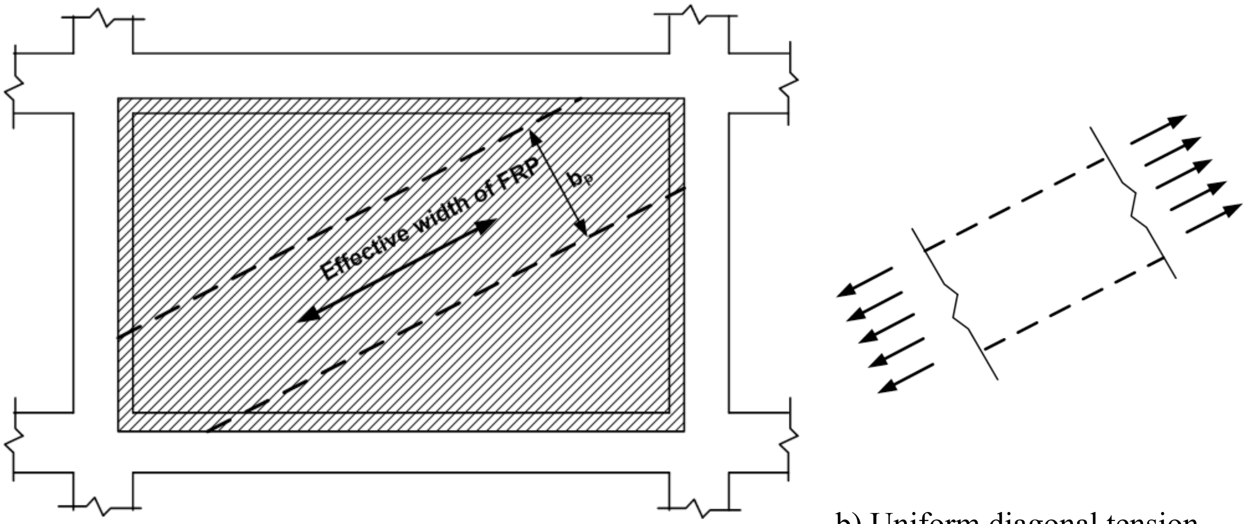
$$L_e = 7.98.c.(n_p.t_p.E_p)^{0.23} \tag{2}$$

The above expression results in an effective bond length ranging approximately between 100 and 200mm, depending on the variables that affect bond strength. It is worth noting that, in design, the minimum bond length of FRP must be at least equal to the effective length of FRP as computed by Eq. 2. In such cases, the ultimate tensile load capacity computed by Eq. 1 reduces to Eq. 3 where the term in the bracket approaches 1.0.

$$P_u = 4.25 \times c \times f'^{\,0.58}_c (n_p t_p E_p b_p)^{0.42} \tag{3}$$

Possible Arrangements of FRP Strips for use in Practice

The experimental research reported in this paper indicates that an increase in the width of surface-mounted FRP strip does not result in a proportional increase in its effectiveness in terms of tensile force capacity. In a typical infilled reinforced concrete frame, diagonally placed FRP sheets may provide the required diagonal bracing against lateral seismic forces as illustrated in Fig. 6. Diagonally aligned FRP sheets covering the entire wall surface may provide sufficient in-plane diagonal tension resistance while also providing the additional benefit of improving out-of plane stability of the wall. However, from the perspective of diagonal tension capacity alone, this may not be economically feasible, since the use of narrow FRP strips may provide just as much diagonal tension capacity with much less FRP material. When narrow strips are used, force resistance per strip may be higher than the contribution of an equivalent width of full FRP coverage. Therefore, the use of multiple narrow strips, as shown in Fig. 7, is worth exploring as an alternative before a surface bonded FRP application is implemented.



a) Surface-bonded FRP on Infill wall

b) Uniform diagonal tension

Figure 6 Development of diagonal tension under lateral seismic loads

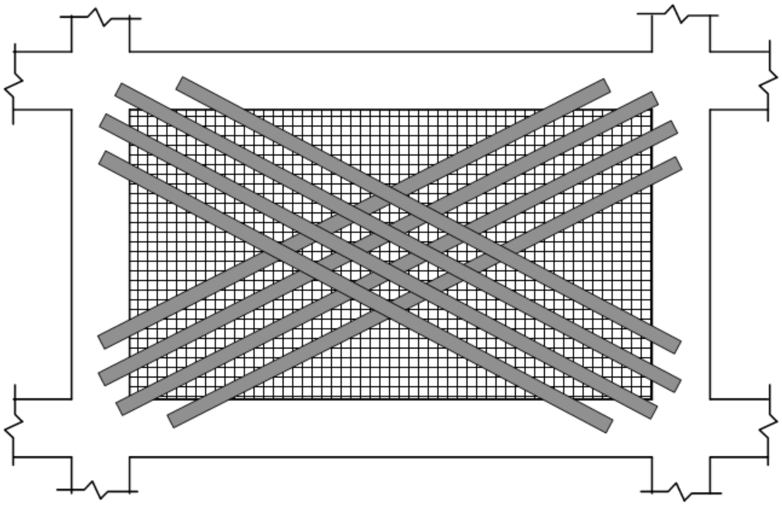


Figure 7 The application of surface-bonded diagonal FRP strips

The effectiveness of selected FRP strip widths are compared in Table 1 in terms of their force resisting capacities. Different strip widths were considered within an assumed 2.0 m effective diagonal width of an infill wall. The strips were either 50 mm or 100 mm in width, and were placed with a clear spacing between 50 mm and 400 mm. The substrate concrete was assumed to have compressive strength of f'_c=30 MPa. The FRP selected was the same as that used in the experimental investigation with the same properties as those specified under "Experimental Study." The results indicate that the use of individual strips reduce FRP consumption while providing higher force resistance.

Table 1. Comparison of the effectiveness of FRP strip widths as diagonal tension elements in a frame-infill wall assembly

Strip Width (mm)	**Strip Spacing (mm)**	**No of Strips**	**Proportional FRP surface area**	**P_u (kN)**	**σ_p Stress (MPa)**
2000	0	1	1.00	75	226
50	50	20	0.50	317	1919
50	150	10	0.25	158	1919
50	200	8	0.20	127	1919
100	100	10	0.50	212	1284
100	150	8	0.40	170	1284
100	400	4	0.20	85	1284

Conclusion

The following conclusions can be derived from the combined experimental and analytical investigation presented in this paper:

- Surface bonded FRP can be used as an effective seismic retrofit strategy in providing lateral bracing to frame elements, while improving out-of plane stability of infill walls. The FRP sheets can also be used for other applications where surface reinforcement may be needed for improved strength.
- The bond strength required between FRP sheets and concrete or masonry substrates can be attained through proper design. The expressions developed for ultimate tensile capacity and effective bond length can be used in designing seismic retrofit applications.
- Surface bonded FRP has a specific effective length, beyond which any increase in length does not result in significant improvements in bond strength.
- The efficiency of surface bonded FRP increases when applied in strips, since the bond strength per unit width of material is higher in narrow strips, as compared with wider surface applications.
- The effect of cyclic load is to increase effective bond length of FRP with corresponding increase in tensile force resistance.
- The effects of concrete strength and FRP sheet stiffness appear to have small effects on surface bond characteristics of FRP.
- More research is needed to establish the surface bond characteristics of FRP sheets for seismic retrofit applications.

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