EFFECT OF BASALT FRP CONNECTOR SIZE AND INSERTION ANGLE ON SHEAR TRANSFER IN PRECAST CONCRETE INSULATED WALL PANELS

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Abstract
Fibre reinforced polymers (FRPs) are advantageous in precast concrete insulated wall panels as they have lower thermal conductivity than traditional steel or concrete shear connectors. Ten double shear push-through tests with basalt-FRP (BFRP) connectors and expanded polystyrene (EPS) insulation were conducted to evaluate the effect of BFRP bar diameter (4 to 8 mm) and insertion angle (30 to 60 degrees, loaded both in tension and compression) on shear resistance. This system is then compared to one with steel shear connectors. In tension, larger FRP connectors tended to fail by pull-out but have higher capacities than equivalently sized steel connectors. However, BFRP connectors have significantly lower capacity (~30% that of tension) in compression; this loading case should be avoided if possible. A simple model that predicts the shear flow of both the connectors and EPS insulation was validated against the experimental results. This model and the experimental results show that adjusting connector insertion angle and connector diameter significantly affects shear flow. Design charts are then presented which allow designers to estimate the shear flow in panels with angled FRP connectors.

1. Introduction
Precast concrete sandwich panels are commonly used as exterior walls in construction. They are usually comprised of two reinforced or prestressed concrete layers that surround an internal layer of foam insulation. Structural continuity between the concrete layers is provided by shear connectors. The connector stiffness and strength heavily influence the design of these walls [1]. Strong and stiff connectors provide ‘fully composite behaviour’ (i.e. the two concrete layers act as a unit); weak and soft connectors provide ‘non-composite behaviour’ (i.e. the layers act independently). Partially composite systems lie between these extremes and represent many panels used on the market. Shear connectors have been presented in many arrangements and materials. This includes but is not limited to: steel trusses, steel pins, concrete blocks, FRP trusses [2], and FRP grids [3]. Fibre Reinforced Polymers (FRP) are often used as shear connectors as they have considerably lower thermal conductivity than steel. They also are considerably stronger and stiffer than plastic connectors [4].

This paper presents an experimental program and a simple numerical model to predict the shear flow capacity of angled Basalt FRP (BFRP) shear connectors. Various BFRP connector insertion angles and connector diameters are studied and compared to a similar system with steel shear connectors.
2. Experimental Program

Ten direct shear push-through specimens were constructed and tested at 2 mm/min using an electromechanical testing frame (Figure 1). The specimens were 500 mm tall, 250 mm wide, and 480 mm thick. These specimens were designed as two back-to-back panels (to create load symmetry) with 60 mm thick concrete layers. The shear connectors were inserted normal to the face of the panel and also on an angle (Figure 1). The foam was debonded from the concrete using a thin plastic sheet in order to isolate the shear response of the connectors. The test matrix, shown in Table 1, shows that the variables are connector diameter (ranging from 4 to 8 mm), insertion angle (ranging from 30 to 60 degrees, in tension and compression), and material (BFRP or steel).

![Figure 1. Specimen dimensions.](image)

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Connector Material</th>
<th>Connector Diameter, mm</th>
<th>Connector Angle, deg</th>
<th>Connector Failure Mode</th>
<th>Test Shear Flow, kN</th>
<th>Model Shear Flow, kN</th>
<th>Test/Model Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-45C-4</td>
<td>BFRP</td>
<td>4</td>
<td>-45</td>
<td>Buckling</td>
<td>2.66</td>
<td>2.00</td>
<td>1.33</td>
</tr>
<tr>
<td>B-45T-4</td>
<td>BFRP</td>
<td>4</td>
<td>+45</td>
<td>Pullout</td>
<td>6.45</td>
<td>4.83</td>
<td>1.34</td>
</tr>
<tr>
<td>B-30C-6</td>
<td>BFRP</td>
<td>6</td>
<td>-30</td>
<td>Buckling</td>
<td>4.18</td>
<td>4.57</td>
<td>0.91</td>
</tr>
<tr>
<td>B-45C-6</td>
<td>BFRP</td>
<td>6</td>
<td>-45</td>
<td>Crushing</td>
<td>4.92</td>
<td>6.28</td>
<td>0.78</td>
</tr>
<tr>
<td>B-60C-6</td>
<td>BFRP</td>
<td>6</td>
<td>-60</td>
<td>Crushing</td>
<td>5.79</td>
<td>6.29</td>
<td>0.92</td>
</tr>
<tr>
<td>B-30T-6</td>
<td>BFRP</td>
<td>6</td>
<td>+30</td>
<td>Pullout</td>
<td>8.19</td>
<td>5.02</td>
<td>1.63</td>
</tr>
<tr>
<td>B-45T-6</td>
<td>BFRP</td>
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<td>+45</td>
<td>Pullout</td>
<td>12.11</td>
<td>8.56</td>
<td>1.47</td>
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<td>B-60T-6</td>
<td>BFRP</td>
<td>6</td>
<td>+60</td>
<td>Pullout</td>
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<td>11.86</td>
<td>1.10</td>
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<tr>
<td>B-45C-8</td>
<td>BFRP</td>
<td>8</td>
<td>-45</td>
<td>Crushing</td>
<td>10.19</td>
<td>11.53</td>
<td>0.88</td>
</tr>
<tr>
<td>B-45T-8</td>
<td>BFRP</td>
<td>8</td>
<td>+45</td>
<td>Pullout</td>
<td>15.68</td>
<td>11.14</td>
<td>1.41</td>
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<tr>
<td>S-45C-6</td>
<td>Steel</td>
<td>5.8</td>
<td>-45</td>
<td>Inelastic Buckling</td>
<td>9.33</td>
<td>10.25</td>
<td>0.91</td>
</tr>
<tr>
<td>S-45T-6</td>
<td>Steel</td>
<td>5.8</td>
<td>+45</td>
<td>Yielding, rupture</td>
<td>10.83</td>
<td>10.41</td>
<td>1.04</td>
</tr>
</tbody>
</table>

* – positive value = connector in tension, negative value = connector in compression

The BFRP used in the panels has a manufacturer reported tensile strength of 1100 MPa and elastic modulus of 70 GPa. The steel shear connectors has a yield strength of 566 MPa, ultimate strength of 650 MPa, and an elastic modulus of 196 GPa, found using tension tests. The concrete was a self-consolidating mix with a design strength, $f'_c$, of 50 MPa.

3. Simplified Shear Model

A relationship is presented in Equation 1 to calculate the shear flow, $V$, based on connector slip, $\delta$.

$$V = \left( \frac{\sqrt{(X \tan \theta + \delta)^2 + X^2} - L}{L} + \frac{3E\phi\delta}{X^2} \right) \frac{4\sin \theta}{L} + \frac{12EI}{L^3} \delta \cos \theta$$

Where $X$ is the foam layer thickness, $L$ is the unsupported connector length through the foam layer, $\theta$
is the connector insertion angle, $\phi$ is the connector diameter, $E$ is the connector elastic modulus, $A$ is the connector cross-sectional area, and $I$ is the connector moment of inertia. The first part of Eq. 1 represents the connector’s axial resistance from truss action while the second term represents the connector resistance from dowel action. Three failure modes were considered based on the maximum connector stress, $f_{\text{connector}}$ (Eq. 2): material failure, pullout (Eq. 3), and buckling (Eq. 4).

$$f_{\text{connector}} = \sqrt{\left( \frac{X \tan \theta + \delta}{L} \right) - L + \frac{3E\phi}{X^2} \delta}$$  \hspace{1cm} (2)

$$f_{\text{bond}} = 0.083 \sqrt{f_c \left( \frac{13.6 X \phi}{\phi} + \frac{C L_e}{\phi} + 340 \right)}$$  \hspace{1cm} (3)

$$f_{\text{buckle}} = \frac{\pi^2 E I}{A (0.66 L)^2}$$  \hspace{1cm} (4)

Where $f_{\text{bond}}$ is the limiting pullout strength from ACI 440 [5], $C$ is the concrete cover (25 mm), $L_e$ is the connector embedment length (Note: if $C / \phi$ term in Eq. 3 exceeds 3.5, it is replaced with 3.5), and $f_{\text{buckle}}$ is the buckling stress of the connector in compression. As $\delta$ increases, $f_{\text{connector}}$ is checked. If $f_{\text{connector}}$ exceeds the rupture stress of the connector material in tension, 30% of the rupture stress in compression [6], $f_{\text{bond}}$, or $f_{\text{buckle}}$ the connector is treated as failed.

4. Results and Discussion

BFRP bar pullout governed failure of the connectors in tension. Larger embedment lengths than those provided are difficult to achieve since the connector would extend outside the concrete layers. However, this capacity may be improved with mechanical anchorage. The steel connectors yielded in tension and buckled in compression. The smaller BFRP connectors in compression bucked while the larger connectors crushed. The maximum shear flow for each test is shown in Table 1. For BFRP connectors in tension, shear flow increased proportionally to connector diameter rather than area. This agrees with the pullout failure mode, which is dependent on connector circumference. In compression, the increase in capacity was proportional to connector area. With regard to insertion angle, the connector capacity increases proportionally to the sine of the insertion angle, illustrating that axial truss action and not dowel action, governs the shear flow of the tested connectors.

The model is compared to the test results in Table 1. The model underestimated pullout strength; this is attributed to a portion of the shear force pushing the bars into the concrete (i.e. bars are not in direct tension). This increases friction (and pullout capacity), most significantly with low insertion angles (e.g. $30^\circ$). However, the crushing capacity of BFRP was overestimated. The relatively slender bars are unsupported across the foam; this leads to higher than predicted bar stresses from 2nd order deflections causing failure to occur at lower than expected loads.

The presented equations were used to predict the response of a range of connector sizes and angles with the results shown in Figure 2. Shear flow increases with connector diameter, particularly at small diameters but less so at larger diameters as the pullout stress decreases (Fig 2(a)). In compression, the capacity is very low with small diameter connectors regardless of insertion angle as BFRP has a very low buckling capacity. The shear flow capacity in compression increases greatly at diameters of 7 mm of more for the angled connectors as the failure mode changes to crushing.

The shear flow capacity of BFRP in tension exceeds that of steel for connectors 7 mm or less. At smaller diameters, BFRP connectors are able to reach higher tensile stress before pulling out than steel’s material strength. With improved anchorage, BFRP could exceed the performance of steel at higher diameters. However, steel outperformed BFRP in compression. This is attributed to steel’s higher buckling resistance (i.e. higher elastic modulus) and higher compression strength.

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3. Conclusions

Ten push through tests using BFRP and steel shear connectors with different insertion angles and diameters were conducted and compared to a simple numerical model. The BFRP bars were controlled by pullout in tension; in compression, smaller bars buckled while larger ones crushed. BFRP outperformed steel in tension with bars 7 mm or smaller in diameter. With improved anchorage, BFRP can outperform steel in tension at larger diameters. However, BFRP was weaker than steel in compression as steel better resists buckling and also has a higher material compression strength. The model predicted the failure modes of the specimens. However, the predicted pullout capacity of the BFRP bars was lower than the test values because of increased bar friction caused by the direction of the shearing force. Crushing capacity was overestimated because 2nd order deflections in the bar are not included, leading to higher than expected bar stresses in compression.

The authors are refining this model against other tests to improve its accuracy. They will then use the design charts to propose simplified equations to design sandwich panels with BFRP shear connectors.

References