AN EXPERIMENTAL INVESTIGATION ON NEAR-SURFACE MOUNTED (NSM) FRP-TO-TIMBER JOINTS

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ABSTRACT

This paper reports the results of a series of tests on timber joints strengthened with near-surface mounted (NSM) pultruded fibre-reinforced polymer (FRP) composite strips. Single-shear FRP-to-timber joints are used to investigate the bonded interface with the test variable being the length of bonded plate. Results include (i) joint behaviour and strength, (ii) load-slip responses, (iii) failure modes, and (iv) FRP plate strains as well as plate efficiencies. An effective bond length is also observed and quantified. Up to 61% of the strain capacity of the plate is utilised and this exceeds a plate utilisation of 24% as measured from tests of FRP-to-timber joints strengthened with externally bonded FRP plates.

KEYWORDS

Bond, debonding, FRP, interface, joints, NSM.

INTRODUCTION

Timber is a popular and versatile construction material (e.g. Breyer et al. 2007). Timber structures may be in need of strengthening and repair due to demands arising from additional loading as well as adverse environmental effects. An effective means to strengthen and repair timber structures is by bonding fibre-reinforced polymer (FRP) composites (Hollaway and Teng 2008). Of particular importance to the success of the FRP intervention is sound design of the FRP-to-timber bonded interface. Research on the strength and behaviour of such interfaces though is limited and this has led to limited design guideline development. Of the limited work reported to date, studies have been mainly confined to externally bonded FRP plates. A recent review of such research is provided in Wan et al. (2013).

Research considering the near-surface mounted (NSM) application of FRP to timber is most limited and such a knowledge gap has led to the study presented herein. An important application of NSM FRP is to historical timber structures in which the FRP needs to be hidden. Figure 1 shows a debonded FRP strip originally applied to a glulam timber beam in a NSM manner (Wan 2013). Central to the rational design of the FRP in this case is sound understanding of the FRP-to-timber bonded interface. There has been some degree of research activity related to the application of NSM FRP to concrete (e.g. Seracino et al. 2007, De Lorenzis and Teng 2007) though and there is expected to be similarities to FRP applied to timber in a NSM configuration.

Figure 1. Timber beam with debonded NSM FRP strip
A series of tests on NSM FRP-to-timber bonded interfaces is reported herein. The test set-up consists of single-shear FRP-to-timber joints of which the lengths of the bonded carbon pultruded FRP strips are varied. Specimen behaviour and failure modes are reported. In addition, an effective bond length is identified. Finally, plate strain efficiencies, in relation to the strain capacity of the FRP strip, are presented. The NSM strengthening system is found to be up to 2.5 times more efficient than externally bonded (EB) schemes applied to the same type of timber. Nineteen tests are reported in this paper. They form part of a much larger program of over 250 tests on EB and NSM FRP-to-timber joints reported in Wan (2013).

**EXPERIMENTAL DETAILS**

**Details of test specimens**

A drawing and photograph of a typical test joint are shown in Figures 2 and 3a, respectively. The lengths of bonded plate ($L_{frp}$) tested were 30 mm, 60 mm, 90 mm, 120 mm, 150 mm, 180 mm and 210 mm. In addition, at least two tests were conducted for each test permutation for repeatability. Hardwood (Camphorwood) was used throughout and timber pieces were selected which were as uniform and similar looking to each other as much as possible. The timber moisture content, which was measured up to a depth of 8 mm with a hand-held digital wood moisture tester, was on average 12.8% for the entire test program of Wan (2013) for hardwood. All FRP plates were sourced from the same roll of pultruded carbon FRP plate of 1.4 mm nominal thickness. The width of FRP strip used in each joint specimen was 15 mm (i.e. Figure 2b) and the dimensions of the saw cut made into the timber to accommodate the FRP strips were 3.5 mm by 18.5 mm. An unbonded zone of 10 mm was maintained at the loaded end of the joint as shown in Figure 2a. The adhesive used was Araldite 420. Following cleaning of the saw cut, adhesive was applied and then the FRP strip was inserted. Testing was conducted at least one week after application of the FRP.

![Figure 2. Test joint configuration](image)

![Figure 3. Test set-up](image)

**Test set-up and instrumentation**

Figure 3b provides a photograph of a test in progress. The timber joints were supported in a holding frame which was in turn supported within a universal testing machine. Monotonic load was applied by displacing the ram of
the test machine at a constant rate of 0.15 mm/min. An electric resistance strain gauge of 10 mm gauge length was installed on the surface of the FRP plate at 40 mm from the adjacent end of the timber joint as shown in Figure 1. Linear variable differential transformers (LVDTs) were positioned at the loaded end of the joint in order to measure the relative slip between the FRP plate and the timber (i.e. LV1 and LV2 in Figure 2). LV1 was generally positioned midway between the strain gauge and the adjacent timber face and it measured the movement of the FRP relative to the test frame. LV2 was positioned 5 mm from the bond line and it measured the movement of the timber relative to the load frame. For calculation of slip between the FRP and timber, the extension of the FRP strip between LV1 and LV2 was taken into account. This extension was calculated from the force in the plate as recorded from the load cell of the universal test machine. LV3 (Figure 2) was positioned to measure out-of-plane movement of the timber. It was mounted 5 mm from the bond line adjacent to the edge of the timber block. The largest LV3 value recorded for the tests reported herein was 0.71 mm. This is considered small. A commonly recognised means to quantify the behaviour of the test joint is by plotting the relationship between applied load and slip. Such results are provided in the results section of this paper.

**Material properties**

_Timber:_ The compressive strength and modulus of elasticity of the hardwood was tested in accordance with BS EN 408:2003 (2006). The test samples were cut from the same lengths of timber used to make the test joints. Nine parallel-to-grain samples were prepared and they were of 30 mm by 50 mm (cross section) and 180 mm height along the grain. Also, nine perpendicular-to-grain samples of dimensions 50 mm by 70 mm (cross-section) and 90 mm height perpendicular to grain were also prepared. The strengths were determined from the peak recorded loads and the measured cross-sectional dimensions of the samples. The elastic moduli were calculated from measurements provided by LVDTs located parallel to each of the four longitudinal sides of the test specimens. The results are provided in Table 1.

<table>
<thead>
<tr>
<th>Grain Direction</th>
<th>Modulus of Elasticity, GPa</th>
<th>Compressive Strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>10.01</td>
<td>49.3</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>0.77</td>
<td>6.4</td>
</tr>
</tbody>
</table>

_FRP:_ The pultruded plate mechanical properties, originally reported in Wang et al. (2011), were tensile strength = 3133 MPa, Modulus of Elasticity = 192 GPa and ultimate strain = 0.0163.

_Adhesive:_ The mechanical properties of the adhesive were tested in accordance with BS EN ISO 527:1996 (1996). Five dog-bone specimens, with least nominal cross-sectional dimensions of 4.6 mm by 9.8 mm, produced a tensile strength = 21.5 MPa, Modulus of Elasticity = 1.72 GPa and ultimate strain = 0.0184. On the whole, the behavior of the adhesive was quite ductile (i.e. the adhesive was capable of supporting sustained load at large strain).

**EXPERIMENTAL RESULTS**

A typical load versus slip response is provided in Figure 3 for the shortest bond length (30 mm) and longest bond length (210 mm) investigated. It is evident that the relationship is relatively linear after the initial settling in period of the test. Debonding initiated at the loaded end of the FRP strip and the load plateau indicates propagation of the debonding crack. Load was lost upon the debonding crack reaching the end of the bonded strip. As expected, the slip and load capacity of the joint increased as the bond length increased. It is interesting to observe that a load plateau existed for short bond length specimens.

Table 2 provides a summary of the peak load applied to each test specimen as well as the average load and standard deviation corresponding to each bond length. Also included in Table 2 is the maximum average plate strain for each test configuration as well as the amount of plate utilisation. Plate strain is back-calculated from each $P_{max}$ result as the strain gauge results were not that reliable. Plate utilisation was calculated by dividing the maximum average plate strain by the ultimate strain capacity of the FRP (i.e. 0.0163). Utilisation peaked at 0.61 (i.e. 1.00 indicates 100 % usage of the plate strain capacity) and remained virtually constant for plate lengths of 150 mm, 180 mm and 210 mm. This indicates that the effective bond length (i.e. Chen and Teng 2001) for this particular test set-up was about 150 mm. In Wan et al.’s (2013) tests on FRP-to-timber joints, in which the same type of FRP plates were externally bonded (EB) onto the same type of hardwood, a bond length of 150 mm produced a strain efficiency of 0.24. This represents a 2.5 times increases (i.e. 0.61/0.24) increase in strain.
capacity of the FRP strip when used in a NSM manner as opposed to an EB manner. The NSM technique yielded higher FRP utilisation due to confinement provided to the FRP by the adjacent timber. Such behaviour has been observed in FRP-to-concrete bonded interfaces.

Figure 3. Typical load-slip responses (Specimens 420PH-30-2, 420PH-210-1)

Table 2. Selected results

<table>
<thead>
<tr>
<th>Identification</th>
<th>Specimen</th>
<th>$P_{max}$ (kN)</th>
<th>Strain</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Individual</td>
<td>Av.$^2$</td>
<td>Sd.$^3$</td>
</tr>
<tr>
<td>Series Specimen</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>420PH30-1~2</td>
<td></td>
<td>13.49</td>
<td>13.62</td>
<td>0.18</td>
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<tr>
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<td></td>
<td>23.34</td>
<td>25.41</td>
<td>2.92</td>
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<td>39.38</td>
<td>29.19</td>
<td>9.06</td>
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<td>32.16</td>
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<td>40.01</td>
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<td>39.29</td>
<td>4.94</td>
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<tr>
<td>420PH210-1~2</td>
<td></td>
<td>39.82</td>
<td>39.83</td>
<td>4.26</td>
</tr>
</tbody>
</table>

1 420PH30-1 = Adhesive + FRP Plate (pultruded) + Hardwood + 30 mm bond length + specimen 1
2 Av.$^2$ = average value
3 Sd.$^3$ = standard deviation
4 Eff.$^4$ = strain efficiency ($\varepsilon$ / 0.0163)
5 Failure modes: T = failure in timber at timber-adhesive interface; I = failure at timber-adhesive interface (very thin layer of timber attached); A = failure at adhesive-FRP interface; W = timber wedge failure

Figure 4 shows the relationship between load ($P_{max}$) and FRP strip bond length for each test specimen. The variation of results within each bond length is evident. This is on account of the variable nature of timber although the scatter increases as bond length is increased. The relatively uniform load at bond lengths up to and greater than 150 mm is evident. This is further evidence of the existence of an effective bond length. For the design of ductile joints, such as the 210 mm bond length result shown in Figure 3, it is desirable to have bond lengths equal to and in excess of the effective bond length. Longer bond lengths will lead to load plateaus extending over longer ranges of slip as is evident in Figure 3.

The final column of Table 2 provides a summary of the failure modes for each set of test specimens. Figure 5 provides typical photographs of the four main failure modes identified, namely (i) Mode T: Timber-adhesive interface failure in the timber (Figure 5a), (ii) Mode I: Timber-adhesive interface failure (Figure 5b), (c) Mode A: Adhesive-FRP interface failure (Figure 5c), and (iv) Mode W: Wedge failure in the timber (Figure 5d). The failure modes were observed over part or a significant portion of the surface of the FRP. The number in brackets besides failure mode T indicates the percentage of timber attached to the debonded FRP strip in relation to the total bond area. This area was calculated with the aid of Matlab (2008) as described in Wan et al. (2013). The percentage of timber left on the debonded surface was at least two thirds of the total bond area for most test joints except for the longest bonded length. The reason for the lower amount for the 210 mm bond length specimen is not clear but it may be due to quality of workmanship. Regardless, the test loads in Table 2 for the 420PH210 specimens are consistent with the 420PH180 and 420PH150 test specimens. Mode T is identified as the preferred failure mode because the properties of the bonded interface can be related to the properties of the
timber. The failure mode in brackets in the final column of Table 2 indicates that particular failure mode was not observed in all test specimens for that particular test configuration.

![Figure 4. Peak failure load versus bond length](image)

**CONCLUSIONS**

The results of a series of tests on FRP-to-timber joints in which the FRP has been applied in a near-surface mounted configuration, have been presented in this paper. Major findings of the research are:
- Identification and classification of several failure modes,
- Identification of the existence of an effective bond length,
- Identification of an adhesive suitable to bond FRP to hardwood, and
- Confirmation of the superior bond strength of near-surface mounted FRP as opposed to externally bonded FRP.

**ACKNOWLEDGEMENT**

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REFERENCES