BEHAVIOUR OF FRP-TO-STEEL BONDED JOINTS

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ABSTRACT

Externally bonded fiber-reinforced polymer (FRP) reinforcement offers an attractive method for the strengthening of structures constructed of various materials. In such strengthened structures, the characteristics of FRP-to-parent material bonded joints play an important role. While extensive research has been carried out on the characteristics of FRP-to-concrete bonded joints, existing work on FRP-to-steel bonded joints is much more limited. In an FRP-to-steel bonded joint, the weak link is the epoxy adhesive, while in an FRP-to-concrete bonded joint, the concrete is the weak link. This paper examines, through a series of pull-off tests in which the FRP-to-steel interface is subjected to direct shear, the parameters that affect the behaviour of FRP-to-steel bonded joints. The test results are first presented and discussed. Based on these test results, the bond-slip relationship relating the interfacial shear stress to the interfacial slip is then investigated, leading to the development of the first ever bond-slip model for FRP-to-steel interfaces.

INTRODUCTION

While extensive research has been conducted on the strengthening of concrete and masonry structures using FRP composites (Teng et al. 2002), the potential of externally bonded FRP composites in strengthening steel structures has been explored only to a very limited extent (Hollaway and Cadei 2003; Xia and Teng 2005). The limited existing work has mainly been concerned with the demonstration of the effectiveness of the FRP strengthening technique for steel structures. Nevertheless, this limited existing work has provided a useful understanding of the overall behaviour and identified possible failure modes of FRP-strengthened steel members, particularly beams.

FRP-strengthened steel beams can fail in a number of different modes. Apart from the conventional failure modes of steel (or steel-concrete composite) beams, FRP-strengthened beams may fail by the tensile rupture of the FRP laminate or by the debonding of the FRP laminate along the FRP-to-steel interface, depending on the beam and strengthening parameters. For convenience of description, the term “interface” is used in two different ways in this paper: (a) it is used to refer to the adhesive layer between the FRP plate and the steel substrate; and (b) it is used to refer to a physical interface such as the FRP-to-adhesive interface and the adhesive-to-steel interface. The precise meaning of the term would be clear within its context.

To be able to understand and model debonding failures in FRP-strengthened steel beams, it is first necessary to understand the interfacial behaviour between FRP and steel, usually through experimental studies on simple FRP-to-steel bonded joints. Indeed, a number of researchers have recently investigated the behaviour of FRP-to-steel bonded joints (Xia and Teng 2005). However, no research has been reported on the nonlinear behaviour of FRP-to-steel bonded joints covering the full range of behaviour and the identification of bond-slip relationships. The present paper presents the results of a study that represents an initial step to fill this gap in existing knowledge.

EXPERIMENTAL PROGRAM

The single-shear pull-off test (Figure 1) was adopted in the present study. This test set-up allows easy monitoring and inspection of the failure process as only one path for debonding is possible. The same test set-up has been widely used in studies on FRP-to-concrete bonded joints (Teng et al. 2002). A test rig (Figure 1a) was carefully fabricated to carry out all the tests reported in this paper. A tensile force was applied to the FRP plate, and the steel block was supported at the loaded end. Appropriate restraints were provided to the steel block to prevent the steel block from uplifting and to minimize any bending in the FRP plate.

Each pull-off test specimen was composed of a steel block bonded with a CFRP plate (Figure 1). The steel block was formed by welding two 12 mm thick steel plates to two 70 mm x 50 mm rectangular hollow sections of 3
mm in thickness as illustrated in Figure 1b. Two pull-off tests were conducted on each steel block, one on each of the two thick steel plates. The two test surfaces of the steel block were sandblasted and cleaned with Acetone to remove any rust, residues and grease to enhance their bonding capability. Ball bearings were used as spacers to achieve the desired adhesive thickness. The ball bearings were adhesive-bonded on the steel plate at six different locations within the bond area before bonding the FRP plate. The bonding of an FRP plate involved the application of an adhesive layer, the placement of the FRP plate, and the pressing-down of the FRP plate to the steel block with a moderate force until the adhesive was sufficiently cured. The adhesive was cured for seven days during which strain gauges were installed on the FRP plate.

![Figure 1 Pull-off test specimen and set-up](image)

### Table 1: Specimen details, test results and predictions

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>Intended/measured adhesive thickness (mm)</th>
<th>Test failure load (kN)</th>
<th>Debonding failure mode</th>
<th>Predictions of the proposed theoretical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>1/1.07</td>
<td>60.5</td>
<td>Adhesive</td>
<td>$L_e$ (mm) $P_{ult}$ (kN) $P_{ult}/Test$</td>
</tr>
<tr>
<td>A-2a</td>
<td>2/1.98</td>
<td>61.7</td>
<td>Adhesive</td>
<td>103.83 59.57 0.965</td>
</tr>
<tr>
<td>A-2b</td>
<td>2/1.84</td>
<td>55.6</td>
<td>Delamination*</td>
<td>102.81 58.98 1.060</td>
</tr>
<tr>
<td>A-4</td>
<td>4/3.88</td>
<td>50.7</td>
<td>Delamination</td>
<td>----- ----- -----</td>
</tr>
<tr>
<td>A-6</td>
<td>6/6.12</td>
<td>53.2</td>
<td>Delamination</td>
<td>----- ----- -----</td>
</tr>
<tr>
<td>B-1</td>
<td>1/0.825</td>
<td>39.4</td>
<td>Adhesive</td>
<td>73.48 38.32 0.972</td>
</tr>
<tr>
<td>B-2a</td>
<td>2/1.90</td>
<td>42.4</td>
<td>Adhesive</td>
<td>82.24 42.89 1.011</td>
</tr>
<tr>
<td>B-2b</td>
<td>2/1.76</td>
<td>38.8</td>
<td>Adhesive</td>
<td>81.40 42.45 1.040</td>
</tr>
<tr>
<td>B-4</td>
<td>4/3.98</td>
<td>47.5</td>
<td>Adhesive/delamination</td>
<td>90.88 47.39 0.997</td>
</tr>
<tr>
<td>B-6</td>
<td>6/6.05</td>
<td>55.9</td>
<td>Delamination</td>
<td>----- ----- -----</td>
</tr>
<tr>
<td>C-1</td>
<td>1/0.875</td>
<td>38.0</td>
<td>Adhesive/delamination</td>
<td>119.85 42.39 1.115</td>
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<tr>
<td>C-2a</td>
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<td>46.8</td>
<td>Adhesive/delamination</td>
<td>129.80 45.91 0.981</td>
</tr>
<tr>
<td>C-2b</td>
<td>2/1.82</td>
<td>46.4</td>
<td>Adhesive/delamination</td>
<td>132.31 46.79 1.008</td>
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<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td>$1.006$</td>
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<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>$0.057$</td>
</tr>
</tbody>
</table>

### Table 2: Material properties of adhesives

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Tensile strength $f_{t,a}$ (MPa)</th>
<th>Young’s Modulus $E_a$ (MPa)</th>
<th>Poisson’s ratio $\nu_a$</th>
<th>Ultimate tensile strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>22.53</td>
<td>4013</td>
<td>0.36</td>
<td>0.5614</td>
</tr>
<tr>
<td>B</td>
<td>20.48</td>
<td>10793</td>
<td>0.27</td>
<td>0.1898</td>
</tr>
<tr>
<td>C</td>
<td>13.89</td>
<td>5426</td>
<td>0.31</td>
<td>0.2560</td>
</tr>
</tbody>
</table>

The effects of the adhesive properties are the focus of the study. The variables considered in the present tests reflect this focus. Three different adhesives were used in the test program. The type of adhesive used for a particular specimen is indicated by the first letter, while the thickness of the adhesive layer is indicated by the
number that follows a hyphen. Two nominally identical specimens are distinguished from each other by letters “a” and “b”. To achieve a wide range of values for the adhesive stiffness, the thickness of the adhesive layer was varied, as the elastic modulus of a commercially available adhesive cannot be readily modified. Four thicknesses were used: 1 mm, 2 mm, 4 mm, 6 mm. It should be noted that the first two thicknesses are realistic, but the last two thicknesses were used to achieve a wide range of the adhesive layer thickness. The bond length ($L_p$) and the plate axial rigidity ($E_{ptp}$) also have a significant effect on the bond behaviour but they were not varied in the test program because their effects are believed to be deducible from existing work on FRP-to-concrete bonded joints (e.g. Cheng and Teng 2001; Yuan et al. 2004; Lu et al. 2005). Details of the parameters varied in the 13 test specimens are listed in Table 1. The CFRP plate used in the test had a bond length of 350mm, a width ($b_p$) of 50mm, a thickness ($t_p$) of 1.2mm and an elastic modulus of 165GPa based on strain measurements on the unbonded part of the CFRP plate in pull-off tests.

For each adhesive, three coupons were tested in tension up to failure. Both longitudinal and transverse strains were measured to determine the elastic modulus and Poisson’s ratio of each adhesive. All three adhesives behaved linearly initially, became slightly nonlinear gradually and failed suddenly by rupture. Their properties are given in Table 2, in which the elastic modulus is the secant modulus at rupture failure.

Along the length of the plate, 12 strain gauges were installed (Figure 1) to determine the axial strains in the FRP plate and to deduce the interfacial shear stresses. Both the adhesive coupon tensile tests and the bond tests were conducted with load control.

**TEST RESULTS AND DISCUSSIONS**

**Failure Modes**

All specimens failed along the FRP-to-steel interface with a wedge of adhesive attached to the FRP plate near the loaded end, as shown in Figure 2. Following the formation of the adhesive wedge, cracks propagated in all specimens along the ‘weakest’ components of the bonded joint, leading to the eventual failure of the joint. Two distinct debonding failure modes were observed: cohesive failure within the adhesive layer (Figures 2a and 2b), and delamination of the FRP plate with the crack propagating within the FRP plate separating some carbon fibres from the resin matrix (i.e. a thin layer of fibres was attached to the intact adhesive layer after failure) (Figure 2c). The occurrence of this plate delamination failure mode indicates that in such FRP-to-steel bonded joints, the adhesive and the FRP-to-adhesive and the adhesive-to-steel interfaces can be stronger than interfaces between fibres and the resin matrix within the FRP plate.

Specimens with 1 mm and 2mm thick adhesive layers failed predominantly by debonding in the adhesive layer adjacent to the FRP-to-adhesive interface (e.g. Figures 2a and 2b). A thin layer of adhesive was attached to the FRP plate after failure. In some specimens, plate delamination occurred after the cohesive debonding crack had propagated over a substantial part of the interface towards the free end of the FRP plate. Since this delamination occurred late in the debonding failure process, it is not taken to be the failure mode of these specimens. That is, these specimens are taken to have failed by cohesive failure in the adhesive layer. In other cases, plate delamination occurred first, followed by cohesive failure in the adhesive layer. Such a failure is taken to be a combination of the two distinct modes (Figure 2d) and denoted as “adhesive/delamination” in Table 1. Failure of the FRP-to-adhesive and adhesive-to-steel interfaces (i.e. pure interfacial debonding) were not observed,
testifying the strong bond capacities of the adhesives to the roughened steel and the FRP plate surfaces. The failure mode of each specimen is given in Table 1. Specimen A-2b should be noted as an exception. In Specimen A-2b, the CFRP plate was detached from the steel block in the vicinity of the loaded end over a distance of 50mm on one side and 70 mm on the other side. This specimen failed by plate delamination rapidly.

In practical applications, adhesive thicknesses of 4 and 6 mm are unlikely to be used, so the plate delamination failure mode appears to be unlikely based on the present tests, although this conclusion is believed to be dependent on the type of adhesive used. For the development of design methods, it is also desirable for failure to occur within the adhesive layer, as there is much greater uncertainty if plate delamination or pure interfacial debonding failures control. Delamination of the FRP plate should be prevented using a strong resin or through-thickness fibres. Interfacial debonding at the FRP-to-adhesive and the adhesive-to-steel interfaces should be avoided by appropriate roughening/treatment of the surfaces of the steel substrate and the FRP plate. For these reasons, the cohesive failure mode in the adhesive layer is focussed on in the remainder of the paper. For a detailed discussion of those joints which failed by plate delamination, the reader is referred to Xia and Teng (2005).

**Load-Displacement Behaviour**

Figure 3 shows the load–displacement curves of four specimens (A-1, A-2a, B-1 and B-2a) which all failed by cohesive failure within the adhesive layer. The slips (or displacements) of the FRP plate were found by integrating the measured strain distribution along the plate length (Xia and Teng 2005). Initially, the displacements of all specimens increase almost linearly with the load. The initial slopes of the load-displacement curves are apparently related to the type and thickness of the adhesive. The initial slopes are higher for the adhesive B specimens whose adhesive had a higher elastic modulus, and are lower for the adhesive A specimens whose adhesive had a lower elastic modulus. Overall, the initial slope decreases with the adhesive layer thickness, but the difference between the two slopes for the two different adhesive layer thicknesses is much smaller than the degree of variation in the adhesive layer thickness. Indeed, assuming that only the adhesive layer is deformable, the predicted slope is far greater than the corresponding experimental slope derived from strain measurements on the top surface of the FRP plate. This is believed to be due to shear deformation within the FRP plate whose shear rigidity is derived from the resin matrix, which is expected to have an elastic modulus of the same order as those of the adhesives used in the present study.

For those specimens with a small adhesive layer thickness, the load–displacement curve becomes nonlinear as the ultimate load of the FRP-to-steel bonded joint is approached due to micro-cracking that initiates at the loaded end. After the initiation of debonding failure when the ultimate load is reached, debonding propagates towards the unloaded end with very limited variations in the load level but substantial displacements, resulting in a plateau in the load-displacement curve. This is similar to the behaviour of FRP-to-concrete bonded joints (Yuan et. al. 2004).

Shear Stress Distributions along FRP-to-Steel Interfaces

Figure 4 shows typical distributions of shear stresses along the FRP-to-steel interface at different load levels for specimens A1 and B1 in the order of displacement. These shear stresses were calculated from the readings of strain gauges mounted on the top surface of the FRP plate (Xia and Teng 2005), so they represent the average shear stresses over strain gauge intervals and are thus smaller than the actual values in the specimen. At a low
load level, the shear stress is the largest at the loaded plate end and then gradually reduces to zero towards the unloaded plate end. As the load increases, the shear stress at the loaded end approaches the local bond strength (i.e. the maximum interfacial shear stress the interface is able to resist). When this local bond strength is reached at the loaded end, the linear stage of the load-displacement curve ends, and the FRP-to-steel interface enters its softening stage, during which the shear stress at the loaded end decreases. When the shear stress at the loaded end reduces to zero, the ultimate load of the specimen is reached. Debonding then propagates towards the free end as the peak shear stress moves away from the loaded end with only small fluctuations in the load level (Figure 4). These stages of development are the same as those described for FRP-to-concrete bonded joints (Yuan et al. 2004).

Figure 4 Shear stress distributions

(a) Specimen A-1

(b) Specimen B-1

Overall, the peak shear stress (i.e. the local bond strength) captured by strain measurements does not vary much along the bond length. The higher peak shear stresses near the loaded end seen in Figure 4 are believed to have been due to the effect of local bending of the plate near the loaded end. The lower peak shear stresses observed for the interface beyond 200 mm from the loaded end (Figure 4) are believed to be due mainly to the larger strain gauge intervals in this region. Figure 4 shows the local bond strengths for specimen A-1 are 4-5 MPa higher than those for B-1. This difference in the local bond strength is more than can be expected based on the tensile strengths of the two adhesives. Visual inspections of the shear stress distributions (Figure 4) show that the effective bond lengths for the two joints (and hence the two adhesives) are about 100 mm for A-1 and 80 mm for B-1 due to a larger strain capacity of adhesive A. These values are only approximate as the strain gauges had a spacing of 25 mm. The higher local bond strengths and the effective bond lengths of adhesive A specimens explain why they have higher ultimate loads than the adhesive B specimens. This also means that the ultimate load of an FRP-to-steel bonded joint does not depend only on the tensile strength of the adhesive but also the strain capacity of the adhesive. That is, the interfacial fracture energy $G_f$ determines the ultimate load, as has been well established for FRP-to-concrete bonded joints (Yuan et al. 2004).
Figure 5 Bond-slip curves of the interface at different distances from the loaded end

Bond-Slip Curves

Figure 5 shows the shear bond stress-slip curves at different distances from the loaded end for specimens A-1 and B-1. The bond-slip curves found from specimens A-1 and B-1 are similar in shape, and the curves for different locations of the same interface are consistent, except near the loaded end where the strain readings are expected to have been affected by local bending of the plate. A bilinear bond-slip model can approximate these experimental curves closely. The slope of the ascending part is very different from the theoretical shear stiffness of the adhesive layer ($G_a/t_a$) due to reasons given earlier in the paper.

BOND-SLIP MODEL

Using the experimental data obtained in the present study, a simple bi-linear bond-slip model was developed as described in this section. The present authors are not aware of any existing bond-slip model for FRP-to-steel interfaces. The proposed bi-linear model (Figure 6) are defined by three key points: the origin (0,0), the peak shear stress point $(\delta_1, \tau_f)$, and the ultimate point $(\delta_f, 0)$, with the area under the curve being the interfacial fracture energy ($G_f$). The coordinates of the peak and ultimate points can be derived from the experimental data.

Based on existing analytical models (e.g. Yuan et al. 2004), the ultimate load of a bonded joint between a thin plate and a stocky substrate block (i.e. the axial rigidity of the substrate block is much greater than that of the bonded plate) is given by

$$P_{uo} = b_f \sqrt{2G_f E_f/t_f}$$

(1)

if the bond length is greater than the effective bond length which is normally the case in practice. For a bilinear bond-slip model, the interfacial fracture energy is given by

$$G_f = 0.5\tau_f \delta_f$$

(2)

so Eq. 1 becomes
\[ P_{\text{adh}} = b_2 \sqrt{E_p f_p \tau_f \delta_f} \]  

(3)

where, \( E_p, b_p, \) and \( t_p \) are the elastic modulus, width and thickness of the FRP plate.

The experimental data indicated that the value of the local bond strength \( \tau_f \) varies with the type of adhesive but does not vary significantly with the adhesive thickness for the same adhesive and the same failure mode. Based on the experimental local bond strengths from those joints which experienced cohesive failure in the adhesive layer at least over part of the interface (i.e. no results from specimens A-4 A-6, and B-6 were included), this local bond strength can be reasonably closely approximated by (Xia and Teng 2005)

\[ \tau_f = 0.8 f_{fa} \]  

(4)

where \( f_{fa} \) is the tensile strength of the adhesive. In deriving this equation, only a single average value was used for each bonded joint. Due to the limited test data available, the dependence of \( \tau_f \) on other parameters, such as the ultimate strain of the adhesive and the width of the FRP plate, is not yet clear and requires further investigations.

The interfacial fracture energy was found to be related to the tensile strength \( f_{fa} \), the shear modulus \( G_a \) and the thickness of the adhesive \( t_{adh} \). A nonlinear function relating the interfacial fracture energy (and hence the product of \( \tau_f \) and \( \delta_f \) ) and the adhesive properties was chosen to approximate the test data, with the unknown coefficients varied to minimise the errors between the theoretical predictions and the test results. This process led to the following expression:

\[ \tau_f \delta_f = 62 \left( \frac{f_{fa}}{G_{adh}} \right)^{0.56} t_{adh}^{0.27} (\text{N} \cdot \text{mm} / \text{mm}^2) \]  

(5)

The above expression provides close predictions of the present experimental ultimate loads (Figure 7). To complete the definition of the bond-slip model, it is proposed that the slope of the ascending part be equated to the shear stiffness of the adhesive layer:

\[ K_s = G_a / t_a \]  

(6)

Therefore, the slip \( \delta_1 \) at the peak shear stress be defined as

\[ \delta_1 = \tau_f / K_s \]  

(7)

![Figure 7 Comparison between test and predicted ultimate loads](image)

The definition of the initial slope of the bond-slip model excludes shear deformation of the resin matrix of the FRP plate, which is believed to be a rational approach as the shear modulus of the resin and the plate thickness varies from one FRP material to another and the deformation of the resin matrix should be accounted for explicitly for each FRP product using its specific properties. This aspect is very important and should be noted when the proposed bond-slip model is used in analysis. This situation contracts with that for FRP-to-concrete bonded joints. For the latter, the deformability of the adhesive layer can generally be ignored as failure usually occurs within the concrete at much lower interfacial shear stresses, and wet lay-up FRP sheets with a thin
adhesive layer between the fibre sheet and the concrete substrate are much more commonly used instead of pultruded FRP plates with a well-defined adhesive layer (Lu et al. 2005).

Since the values from Eq. 7 for $\delta_j$ is generally very small compared to values of $\delta_j$, the effective bond length for a bond-slip model with a rigid ascending branch followed by a linearly ascending branch, which is given by (Yuan et al. 2004)

$$l_e = \frac{\pi}{2\sqrt{f_j/E_j\delta_j}}$$

A comparison of the effective bond lengths and the ultimate loads from the present tests with those predicted using the present bond model is given in Table 1. Very close agreement is seen.

CONCLUSIONS

This paper has presented a study into the interfacial behaviour of a pultruded FRP plate bonded to a steel member, which is the basis for understanding debonding failure mechanisms in FRP-plated steel members. Results from a series of pull-off tests have been presented and discussed to understand the effects of the properties and the thickness of the adhesive layer on bond behaviour. Based on detailed strain measurements, a bond-slip model has been proposed for FRP-to-steel interfaces. The results and discussions presented in the paper allow the following conclusions to be made:

- The thickness of the adhesive layer has a significant effect on the failure mode. When an adhesive layer of realistic thickness (< 2mm) is used, debonding is likely to occur within the adhesive layer with a ductile failure process, but when a thick adhesive layer is used, debonding is likely to occur by plate delamination. Plate delamination is a brittle failure mode and should be avoided in practice.
- For joints that fail by debonding in the adhesive layer, the local bond strength of the FRP-to-concrete interface is closely related to the tensile strength of the adhesive and does not depend on the adhesive layer thickness, but the interfacial fracture energy depends on both the ultimate tensile strain of the adhesive (i.e. the elastic/shear modulus for the same tensile strength) and the adhesive layer thickness.
- The slips found from strain measurements on the top surface of the FRP plate includes shear deformation of the resin matrix of the FRP plate, as the shear modulus of the resin matrix is of the same order as that of the adhesive layer.
- For joints that fail by debonding in the adhesive layer, the bond-slip curves can be very closely approximated by a bi-linear model. Based on this observation, a simple bi-linear bond-slip model has been proposed, which leads to accurate predictions of the ultimate loads and effective bond lengths of the present pull-off test specimens. Since the present tests covered only a limited range of variables, further research is needed to assess and improve the accuracy and applicability of the proposed bond-slip model.

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