PRELIMINARY BOND-SLIP MODEL FOR CFRP SHEETS BONDED TO STEEL PLATES

S.Fawzia, X.L. Zhao, R. Al-Mahaidi
Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia

S.H. Rizkalla
North Carolina State University, Raleigh, North Carolina, USA

ABSTRACT

Carbon fiber reinforced polymer (CFRP) sheets have established a strong position as an effective method for innovative structural rehabilitation. However, the use of externally bonded CFRP in the repair and rehabilitation of steel structures is a relatively new technique that has the potential to improve the way structures are repaired. An important step toward understanding bond behaviour is to have an estimation of local bond stress versus slip relationship. The current study aims to establish the bond-slip model for CFRP sheets bonded to steel plate. To obtain the shear stress versus slippage relationship, a series of double strap tension type bond tests were conducted. This paper reports on the findings of the experimental studies. The strain and stress distributions measured in the specimens for two different bond lengths. The results show a preliminary bi-linear bond-slip model may be adopted for CFRP sheet bonded with steel plate.

KEYWORDS

FRP Sheet, Bonding, Bond-Slip Model, Slip, Shear Stress.

1. INTRODUCTION

Successful use of carbon fiber-reinforced polymer (CFRP) materials for strengthening concrete structures has already been established [e.g. ACI Committee 440F 2002, Teng et al 2002, Oehlers and Seracino 2004, Pham and Al-Mahaidi 2006]. However, the development of the system for strengthening steel structures with CFRP materials is limited. More strengthening materials are needed to achieve a significant strength increase as steel is much stronger than concrete, especially in tension. But as more strengthening material is added the bond stresses become more critical. There have been relatively fewer studies on the bond stress and slip relationship between CFRP sheet and steel structures.

The bond-slip relationship relating the interfacial shear stress to the interfacial slip for steel structure strengthened by CFRP plate was recently studied by Xia & Teng (2005). In this paper a local bond-slip relationship is proposed from the experimental results for CFRP sheets bonded to steel structure. The possibility of finding local bond-slip relationship using long bond length (say twice the effective bond length or higher) is strictly related to the consideration of the distribution of slip and bond shear stress along the bond length.

2. EXPERIMENTAL PROGRAM

2.1 Bond specimen and surface preparation
The tensile specimen was composed of mild steel plate bonded with three layers of CFRP sheet on both sides. Figure 1 shows the schematic specimen configuration. A careful, meticulous approach is necessary when dealing with bonding since it may be difficult to verify the quality of the bond. Moreover, due to the local effect of bond stresses, any local defect of the bond may result in complete debonding of the applied strengthening material. The steel plate was 6mm thick and 900 mm long in total. The steel plate was ground at 45° by angle grinder (FH38A36S-BF41). After grinding, the steel plate was cut into two pieces and then added together by applying small amount of adhesive at the cross section. After that the plate was cleaned by Acetone. Adhesive was first applied on the surface of steel plate by brush. Then a piece of fiber sheet, which had been cut beforehand into prescribed sizes using scissors, was placed with the fiber side down onto the coating and generally smoothed down by hand. After that, the surface of the sheet was rolled over along the longitudinal direction of the fibers using a ribbed roller to impregnate resin into the fibers and removed any air bubbles. Rolling was continued until the resin was squeezed out between the fibers. Same steps were followed to bond two more layers of fibers. The specimen was cured at least one week and then postcured for 24 hours at 70°C.

2.2 Material properties

Measured modulus of elasticity, tensile stress and thickness of CFRP sheet are 250 GPa, 1710MPa and 0.176mm, respectively. The modulus of elasticity and tensile stress of adhesive are 1900MPa and 32 MPa, respectively.

2.3 Instrumentation

Sixteen strain gauges were attached to each test specimen. Figure 1 shows the location of each gauge. Ten strain gauges were placed along the length at every 25mm on one side of the CFRP sheet to capture the longitudinal strain development along the bond length. Four strain gauges were placed on the backside of the specimen at every 50mm to act as “backup” gauges and for comparison with the primary gauge readings. Two additional strain gauges were attached to the steel plate before the initiation of the CFRP sheets and were used to determine the actual load applied to the steel plate during testing.

![Figure 1: A Schematic of specimen and strain gauge locations](image)

2.4 Failure mode and test results

Test results, together with the failure modes are presented in Table 1.

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond length (mm)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Overall thickness of specimen (mm)</td>
<td>9.50</td>
<td>9.75</td>
<td>9.82</td>
<td>9.28</td>
<td>9.38</td>
<td>9.46</td>
</tr>
<tr>
<td>Ultimate load (kN)</td>
<td>89.6</td>
<td>97.2</td>
<td>77.5</td>
<td>92.6</td>
<td>71.6</td>
<td>99.6</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Bond</td>
<td>Bond</td>
<td>Bond</td>
<td>Bond</td>
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<td>Bond</td>
</tr>
</tbody>
</table>
3. Strain and interfacial stress distribution

The data obtained from the strain gauges at the top layer of CFRP was used to create strain versus distance (from the steel joint) plots. The top strain is different from the average composite strain as the strain could vary across the layers of the composite. This variation was measured experimentally for circular tube strengthened by CFRP sheet [Fawzia et al. 2004]. In this study it was assumed that the measured strain was representing the average CFRP strain. The distributions of strain along the bond length for different load levels are plotted in Figure 2 for Specimen S6. The distance in the figure is measured from the joint location. At low load levels, the distributions show a gradual decline from the peak near the steel joint to the other end. As the load increases up to 98.3kN, the strain values increase and the peak strain gradually shifts away from the joint. At low levels, the distributions have the largest slope near the steel joint. As the load increases, the maximum slope shifts away from the joint. This means that redistribution of the bond stress along the bond length occurs as a result of changes in the state of bond.

4. BOND-SLIP MODEL

The measured strain distribution along the bond length was used by integration to calculate local slips. Actually this local slip is the relative displacement between the CFRP sheet and the steel plate. Calculated bond stresses and slips are combined to obtain the local bond-slip curves. Bond-slip curves obtained from experimental data can be approximated as a bi-linear shape (Lu et al., 2005). These curves have a linear ascending branch followed by a linear descending branch. A schematic view is presented in Figure 4 which can be defined by three parameters $\delta_1$, $\tau_f$ and $\delta_f$. The initial stiffness of the bond-slip curve is high, representing linear elastic state. Initiation of interfacial softening stage means load continues to increase as the length of the softening zone increases. The ultimate load is first attained at the end of this stage and starts propagation of debonding. These three stages can be identified from load-displacement behaviour. The local bond slip relationship is reasonably consistent between different locations on the same specimen.
5. CONCLUSIONS

The following conclusions can be drawn from this paper.

1. Strain distribution profiles show that strain level is significant over a limited bond length.
2. When debonding occurs at most highly stressed end, less or almost zero stress is transferred at that end and the maximum shear stress location shifts towards the unloaded end of the specimen.
3. The bond-slip curve may be approximated as a preliminary bilinear model. More reliable peak shear stress and slip values will be produced after analysing more test data.
4. The limitations of such bilinear model mentioned elsewhere in the paper are

Depend on the values of $\delta_1$, $\tau_f$ and $\delta_f$. One type of CFRP, One type of adhesive, Bond failure happened around 53% of FRP rupture strain, Only two types of bond length has considered.

6. REFERENCES

1. ACI Committee 440 (2002), Guide For The Design And Construction Of Externally Bonded FRP Systems For Strengthening Concrete Structures. American Concrete Institute, Detroit MI.