Third International Conference on FRP Composites in Civil Engineering (CICE2006)
December 13-15 2006, Miami, Florida, USA

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 grinded at 45^0 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 70^0C.

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.

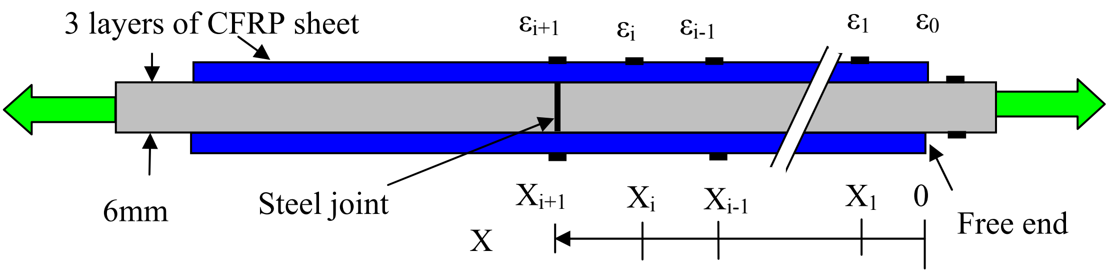


Figure 1: A Schematic of specimen and strain gauge locations

2.4 Failure mode and test results

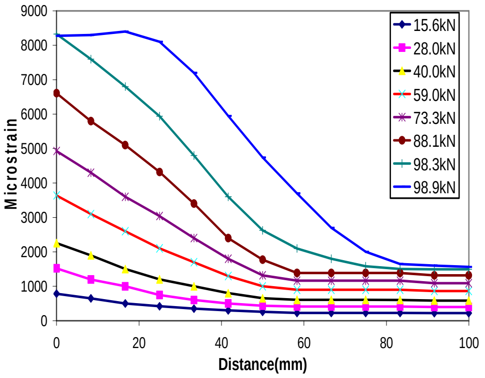
Test results, together with the failure modes are presented in Table 1.

Table 1: Test results

Test specimen	S1	S2	S3	S4	S5	S6
Bond length (mm)	250	250	250	200	200	200
Overall thickness of specimen (mm)	9.50	9.75	9.82	9.28	9.38	9.46
Ultimate load (kN)	89.6	97.2	77.5	92.6	71.6	99.6
Failure mode	Bond	Bond	Bond	Bond	Bond	Bond

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 el 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.



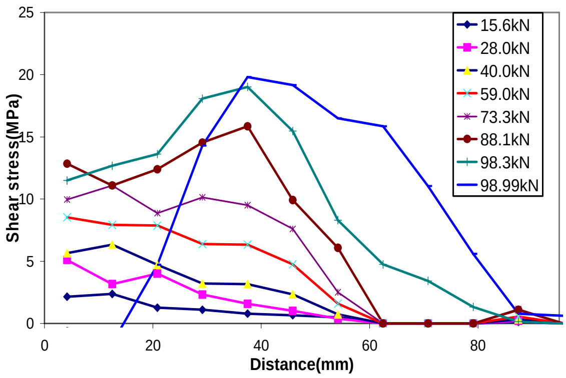


Figure 2: CFRP strain distribution

Figure 3 : Shear (bond) stress distribution

The average experimental shear stress between the two strain gauges were calculated using the relationship $\tau = \frac{E_f(\varepsilon_{f,i+1} - \varepsilon_{f,i})t_f}{X_{i+1} - X_i}$, where E_f and t_f are the CFRP elastic modulus and thickness respectively and $\varepsilon_{f,i+1}$, $\varepsilon_{f,i}$ are the CFRP strains and X_{i+1}, X_i are the distance between strain gauges according to Figure 1. The shear stress distribution along the distance away from the "steel joint" is shown in Figure 3. It should be pointed out that there is a gap between the two steel plates. The location of the "steel joint" is equivalent to the "loaded edge" in the set up of testing bond between CFRP plate and steel (Xia and Teng 2005). The theoretical stress distribution for bond between CFRP and concrete can be found in H.Yuan et al. (2004). The theory shows that at loaded edge the shear stress is zero when it reaches peak load indicating occurrence of debonding. It can be seen from Figure 3 that when the load is less than 59kN, the peak shear stress is located at the steel joint. The location of the peak shear stress moves away from the "steel joint" as the load increases further. The shear stress at the steel joint becomes zero when the maximum load occurs indicating the occurrence of debonding.

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 δ_1, τ_f and δ_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.

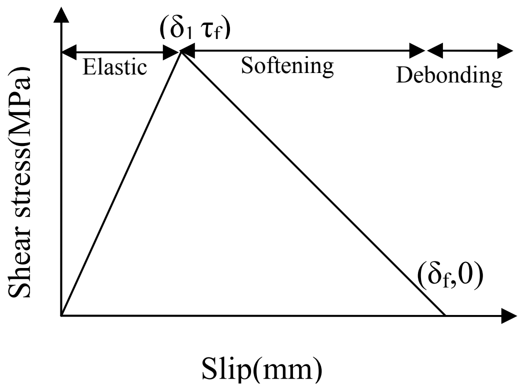


Figure 4 Bond slip model approximation

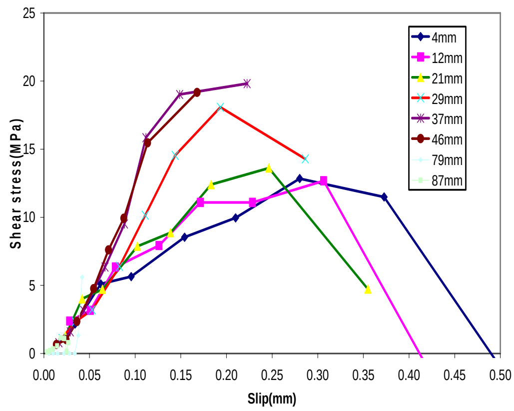


Figure 5 Bond slip curve (Specimen S6)

Figure 5 shows the stress vs slip curves (specimen S6) with bond length of 200mm. It seems that a bi-linear model may be adopted to represent the bond-slip relationship for CFRP sheet bonded with steel plate. However, the three parameters (δ_1, τ_f and δ_f) in bond-slip model are to be determined after processing all the test data. These will be compared with those given by Xia & Teng (2005) in the near future.

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 δ_1, τ_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.
2. Fawzia, S., Zhao, X. L., Al-Mahaidi, R. and Rizkalla, S. (2004).Investigation Into The Bond Between CFRP And Steel Tubes, The Second International Conference on FRP Composites in Civil Engineering,CICE2004, December, Adelaide,. pp733-739.
3. H.Yuan, Teng, J. G., Seracino, R., Z.S.Wu and J.Yao. (2004).Full-Range Behaviour Of FRP - To-Concrete Bonded Joints. Engineering Structures.Vol.26: pp553-565.
4. Lu,X.Z., Teng, J.G. Ye,L.P. and Jiang, J.J.(2005) Bond-Slip Models For FRP Sheets/Plates Bonded To Concrete. Engineering Structures.Vol.27:pp 920-937.
5. Oehlers, D.J. and Seracino, R. (2004), Design Of FRP And Steel Plated RC Structures – Retrofitting Beams And Slabs For Strength, Stiffness And Ductility, Elsevier, Oxford, UK
6. Pham, H. B. and Al-Mahaidi, R. (2006), "Prediction Models For Debonding Failure Loads Of CFRP Retrofitted RC Beams", Journal of Composites for Construction, Vol. 10, No. 1, pp. 48-59
7. Teng, J. G., Chen, J. F., Smith, S. T. and Lam, L. (2002).FRP-Strengthened RC Structures, John Wiley and Sons Ltd,UK.
8. Xia, S. H. and Teng, J. G. (2005).Behaviour of FRP-to-Steel Bonded Joints. Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005). International Institute for FRP in Construction, Hong Kong: pp 419-426.