Performance of different types of FRP sheets bonded to concrete using flexible adhesive

Hesham M. Diab

Civil Engineering Department, Assiut University, Egypt
heshamdiab2@yahoo.com

Abstract: De-bonding problems stand as a critical barrier against a wide range of usages of FRP composites in structural strengthening and repairing applications. Results of an experimental campaign on FRP-concrete debonding are presented in this study. Specimens with different types of FRP sheets bonded to concrete prism using flexible adhesive were conducted to determine the effective bonding length and ultimate bond capacity of FRP-concrete interface. The experimental results from double lap shear specimens indicated that the flexible adhesive has increased both of the effective bonding length and the ultimate bond capacity of FRP-concrete interface. Increase of fracture energy of FRP-concrete interface has been clearly observed due to flexible adhesive for all different types of FRP sheets. Analytical models available in the literature were adopted to evaluate the bond strength and the effective bond length of the experiment results in this study. Consequently, the existing models need to be modified to consider the type of adhesive layer. A unique feature of the present study is that a simple modification done to the most popular bond strength model, Chen and Teng model (2001), to predict both bond strength and effective bonding length considering the type of adhesive layer. The validation of bond strength model is supported via experiment test results.

Key words: Bond strength model, Flexible adhesive, FRP sheet, Concrete.

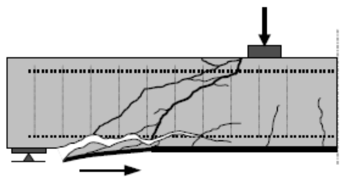
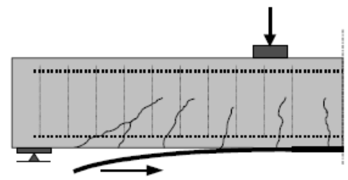
Introduction

External bonding of FRP sheets/plates is an effective and popular method for the rehabilitation of reinforced concrete structures. The mechanical performance, including the strength of the external bonded FRP structural system, is often determined by the bond between FRP composites and concrete. The bond interface, FRP-concrete interface, is usually the weakest link, and debonding at the interface is usually the critical failure mode. Debonding initiation in beams strengthened with FRP composites generally take place in regions of high stress concentration at the concrete-FRP interface. These regions include the ends of the FRP reinforcement, and those around the shear and flexural cracks (Buyukozturk et. al. 2002). Figure 1 shows the fundamental debonding mechanisms that may result in premature failure of FRP strengthened beams. Thus, determination the bond capacity of the FRP-concrete interface is an important subject, and has attracted extensive research till now (Caggiano at. al. 2012, Wu at. al. 2012, Wu at. al. 2012, Tuakta and Büyüköztürk 2012).

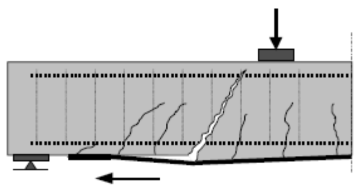
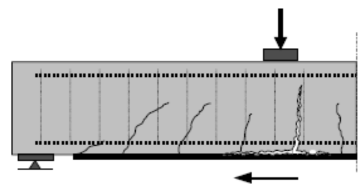
Based on the extensive tests, researchers concluded that bond capacity is affected mainly by mechanical and physical properties of concrete, thickness and stiffness of the FRP, thickness of the adhesive, and the bonded length (Chen & Teng 2001, Neubauer & Rostasy 1997, Wu at. al. 2009). However, some researchers concluded that thickness of the adhesive has negligible effect on mean and peak shear stresses (Hamoush and Ahmed 1990, Nakaba at. al. 2001). Analytical models have been proposed in order to predict the behaviour and the ultimate bond strength of the FRP-strengthened system. It is interesting to note that most of the existing models, which are in reasonable agreement to experimental results(Chen & Teng 2001, Neubauer & Rostasy 1997, Wu at. al. 2009), neglect the adhesive layer properties.

Indeed, a number of researchers investigated the effect of flexible adhesive on the bonding of FRP sheets (Xia & Teng 2005, Dai at. al. 2005). Dai et. al.(2005) provided a summary report on the flexible bonding system. The contents included the bond characteristics of FRP/concrete joints, strength and ductility of FRP strengthened

RC beams. It is concluded that the flexible bonding system with a sufficient long anchorage can achieve higher bond capacity and a ductile failure. Moreover, Dai and Ueda (2003) considered the effect of adhesive layer stiffness by considering different thicknesses of the adhesive layer and they concluded that the use of adhesive with lower stiffness may lead to higher bond capacity. On the other hand, Xia and Teng (2005) studied the interfacial behaviour of FRP plates bonded to steel member using different adhesive types. It was concluded that properties of adhesive have a significant effect on the bond capacity of FRP-steel joints.

(a) Cover debonding (b) FRP debonding from laminate end

(c) FRP debonding from flexure-shear cracks (d) FRP debonding from flexural cracks

Figure 1: Debonding failure mechanism of FRP strengthened beams

So far, none of the existing proposed models have gained general acceptance by the research community due to their limited success and applicability. Continued research is needed in this area to understand and model debonding failures in FRP strengthened concrete structures. On the other hand, most existing models were developed from results of single or double test methods of FRP-bonded concrete blocks using ordinary adhesive (one kind of epoxy). In turn, most of these bond strength models neglect the effect of adhesive properties and therefore the corresponding applicability to the structural system remains challenged. A reliable and efficient model should be established through a comprehensive understanding of adhesive layer type role on FRP-concrete strengthening systems.

Experimental program

A series of double-lap shear specimens with adhesively bonded FRP sheets were conducted to investigate the bond capacity, effective bond and fracture energy of flexible adhesive FRP-concrete interface.

Material and specimens details

Double-lap shear specimens with concrete dimensions 100x100x450 mm^3 have been used in this study. Details of the test specimens are shown in **Photo 1**. The compressive strength of concrete after 28 days was 40.0 MPa.

FRP sheets:-

FRP sheet layers were bonded to both sides of the concrete blocks along the axial direction and the bonded length was kept fixed at 250 mm, for all specimens. Two different types of FRP sheets were adopted in this study.

The mechanical properties of the FRP composites and their nominal thickness of FRP fibers are shown in Table 1. Properties of Fibers are provided by manufacturers.

Table 1: Summary of mechanical properties of different fiber sheets

Types of Fibers	Fiber Aerial Weight (g/m2)	Thickness (mm)	Modulus of Elasticity (MPa)	Tensile Strength (MPa)	Rupture Strain (%)
Carbon fiber	300	0.167	230 x103	3400	1.48
Basalt (BUF7-300)	300	0.17	91.0 x103	2100	2.6

Adhesive

FRP sheets were bonded to the concrete prisms with a flexible type of Epoxy resin. The brand of adhesive used in this study is CN-100 for flexible adhesive layer. The CN-100 epoxy has a modulus of 0.39 GPa, a tensile strength of 11.8 MPa and an elongation of 50%.

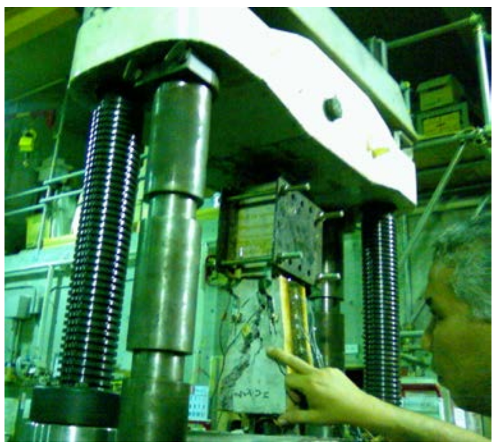


Photo 1: Experimental Set-Up

Instrumentation and Testing Procedure

Seven strain gauges with 6 mm length were mounted on FRP sheets to monitor debonding deterioration along FRP-concrete interface. During each test, the global slip, which is defined as the relative displacement between the two concrete blocks, was measured using four clip strain gauges that were attached on free sides of concrete prism. Two clip strain gauges attached near each FRP sheet as shown in **Photo 1**. Tensile load is applied by pulling both ends of steel bars embedded in the concrete prism, with rate 2 kN per minute until failure.

The specimens were labeled within alphanumeric designation (Table 2) depending upon the type of the FRP sheets, adhesive layer and number of FRP sheet layers. The number following the hyphen represents the number of specimen. Two types of FRP composites were considered in this study; carbon fiber reinforced polymer, CFRP, and basalt fiber reinforced polymer, BFRP. The test temperature was about 22-24 ^{o}C. Table 2 summarizes the number of specimens, their parameters and their results.

Experimental Results and Discussions

The complete experimental results for all specimens are listed in Table 2. The ultimate displacement is defined as the value of relative displacement between the two concrete blocks at the maximum load. The effective bonding length (Le) is defined as the distance from the pre-crack of prism specimen to the position where 97% strain of the value at the pre-crack occurs (Yoshizawa et. al. 2000) The interfacial fracture energy, Model II, Gf, represents the total external energy supply, per unit of area, required to create, propagate and fully break a crack along the FRP-concrete interface. The FRP-concrete interface is determined from the following equation:-

$$G_f = \frac{P^2}{2 b_f^2 E_f t_f} \quad (1)$$

Where P is the tensile force of one lap FRP laminate, b_f , E_f and t_f are width, modulus of elasticity, and thickness of the FRP sheets, respectively.

Table 2: Specimens' data and key results from bond tests

Specimen	Type of FRP Sheets	No. of FRP Sheets	Ultimate Load (kN)	Max. Displ. (mm)	Fracture Energy (N/mm)	Effective Bonding Length	Failure Mode
BFRPL1-1	Low adhesive (CN-100)	1	24.23	1.74	1.94	110	(B)
BFRPL1-2		1	21.90	2.6	1.58		(C)
BFRPL1-3		1	17.40	1.99	1.00		(B)
BFRPL2-1		2	19.89	1.51	0.65	210	(B)
BFRPL2-2		2	22.25	1.41	0.82		(B)
BFRPL2-3		2	23.60	1.48	0.91		(B)
BFRPL3-1		3	32.45	1.39	1.16	>250	(B)
BFRPL3-2		3	44.19	1.75	2.15		(B)
BFRPL3-3		3	36.80	1.63	1.49		(B)
CFRPL1-1		1	43.8	1.57	2.50	200	(A)
CFRPL1-2		1	41.6	1.24	2.25		(C)
CFRPL1-3		1	37.65	1.35	1.85		(C)
CFRPL2-1		2	48.4	0.91	1.52	250	(D)
CFRPL2-2		2	44.62	1.10	1.30		(D)

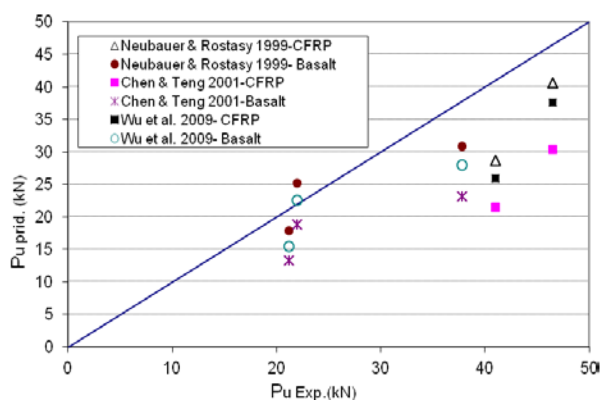


Figure 2: P_u predicted versus P_u experiment for different types of FRP composites using Flexible adhesive layer

Bond Strength of the FRP-Concrete Interface

Load carrying capacity is an important reference for selecting the optimum bonding adhesive. There was a clear reinforcement action which was achieved by application of low adhesive with different types of FRP sheets. Figure 2 shows experimental ultimate bond strength versus predicted ultimate bond strength. The bond strengths were calculated using the most accurate and appropriate bond strength models which were proposed by Wu et al. (2009), Chen and Teng (2001), and Neubauer and Rostasy (1997). Details of these models can be found in their references.

It is clear that these models underestimate the bond strength of all specimens except one specimen which has low FRP stiffness, i.e. BFRPL2 and BFRPL1. It seems that the accuracy of the bond strength model depended on the type of adhesive layer as shown in Figure 2. These results emphasized that low adhesive layer can be successfully used to increase the bond capacity of the FRP-concrete interface. The improvement in ultimate strength for specimens using flexible adhesive layer was likely attributable to the larger ductility of the adhesive.

CFRPL1-1 (A) BFRPL1-3 (B) CFRPL1-2 (C) CFRPL2-2 (D)

Figure 3: Typical failure mode of FRP specimens

Failure Modes

In the previous study, debonding along FRP-concrete interface has been observed to be the failure mode for most of specimens which were bonded with ordinary epoxy (EF-E3P) as an adhesive layer. This type of debonding initiated by shear failure in the concrete near the loaded end and followed by the debonding along the weakest component of the bond joint (failure mode A).

In the present study, in addition to failure mode A, three other different failure modes are indentified from the experimental investigation of the specimens used flexible epoxy, CN-100, as an adhesive layer as shown in Figure 3. The failure mode “B” has a debonding at interface between epoxy and epoxy resin and failure mode “C” is also observed due to the rupture of the FRP composites while failure mode “D” results due to crushing of the concrete block along the steel bar of specimens. Failure mode “D” has the maximum load carrying capacity. Therefore this capacity is depended on the strength of concrete and shape of specimens as the failure is in concrete rather FRP-concrete interface. Consequently, the number of CFRP sheets was not increased than two layers.

For BFRP specimens with low adhesive layer; although higher load capacity is observed, but the failure mode B occurs instead of failure of mode A as observed in BFRP specimens with ordinary adhesive (Diab and Wu 2009). On the other hand, specimens with the higher Young’s modulus of the FRP sheet (CFRP) and the lower adhesive stiffness will result in the maximum bond capacity of the FRP-concrete interface. It can be concluded that the load carrying capacity and the failure mode of the FRP-concrete interface not only depends on the FRP sheet stiffness, bond length, surface treatment and concrete strength as mentioned in previous studies (Mazzotti at. al. 2008), but also depends on the type of adhesive layer stiffness which is the important factor and should be taken into consideration.

Interfacial Fracture Energy

Equation 1 can be used to predict the interfacial fracture energy G_f (model II). The values of interfacial fracture energy for each specimen are shown in Table 1. It is observed that the interfacial fracture energy of specimens of flexible adhesive layer fall within the range between 0.82 and 2.25 N/mm. On the other hand, previous studies concluded that the interfacial fracture energy of FRP-concrete interface using ordinary adhesive falls within the range between 0.68 and 1.09 N/mm (Mazzotti at. al. 2008, Teng at. al. 2005). Consequently the fracture energy also depends on the properties of adhesive layer.

Effective Bond Length

Figure 4 shows a comparison between predicted effective bonding length ($Le_{Prid.}$) and experimental effective bonding length which was determined from experiment results ($Le_{Exp.}$) as mentioned previously. Such figure shows that the effective bonding lengths of specimens with flexible adhesive layer are higher than those obtained using the previous mentioned models. The effective bonding length of specimens using flexible adhesive is nearly equal or greater than bond length as shown in Table 1, except specimens BFRPL1-1,2,3. Therefore the bond capacity of these experimental specimens may be less than the actual bond strength if the bond length is greater than the effective bond length. Nevertheless, clear increases in bond capacities were observed for CFRP specimens which are of bond lengths less than the effective bond lengths.

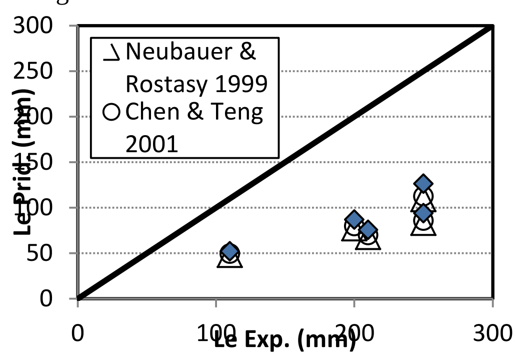


Figure 4: Le predicted versus Le experiment for different types of FRP composites using Flexible adhesive layer

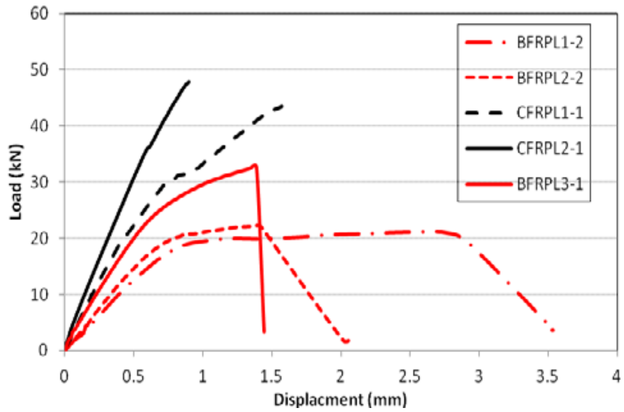


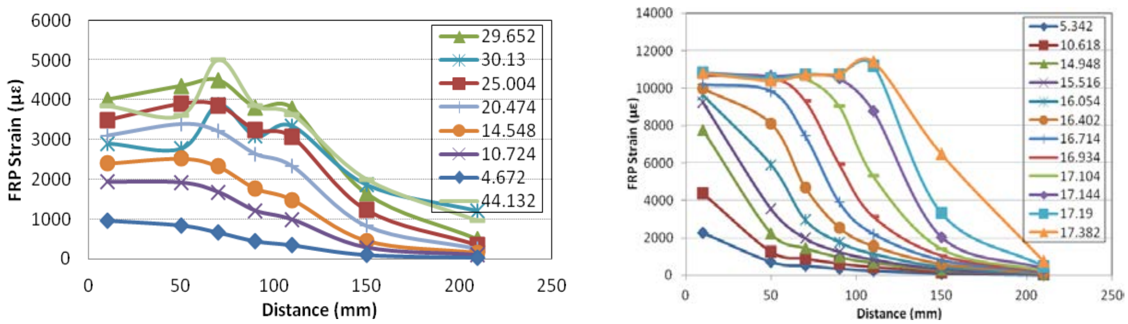
Figure 5: Load-Slip Relationship of Specimens

Load-Displacement Behavior

Figure 5 shows the typical load-displacement relationships of flexible adhesive layer's specimens of different types of FRP sheets (Carbon and Basalt). The slips (or relative displacement between two concrete prisms) of the FRP sheets represent the average values of the four clip gauges attached to each specimen. Such figure shows that the bond capacity of BFRPL1-2 and BFRPL2-2 specimens had reached its maximum carrying capacity as the Load-displacement curve moved horizontally after debonding. However, in the case of other specimens, the bond Force still showed increasing tendency after debonding initiation. This behaviour confirms that the effective bonding length of these specimens is greater than the bond length as mentioned previously. Therefore, it is possible for these specimens to achieve higher bond capacity if the bond length is increased. Specimens with flexible adhesive layer improved ductility of the FRP-concrete interface when the bond length is longer than the effective bonding length.

FRP sheet strain distribution

Figure 6(a and b) shows typical FRP sheet strain distribution along the bonded length at different load levels for CFRPL2-2 and BFRPL1-3 specimens, respectively. Profile of FRP strains is almost linear and the strains decrease smoothly along the bonded length within a distance range from 100 to more than 200 mm based on the FRP sheet stiffness. These results are dissimilar to those already reported in other papers (Mazzotti at. al. 2008) for ordinary adhesive layer. By comparing between the two FRP strain profiles, it is noticed that the effective bonding length of BFRPL1-3 is less than the bond length while the effective bonding length of CFRPL2-2 is longer than the bond length. According to these results, the adhesive layer with low stiffness increases the effective bonded length which results in the redistribution of bond stresses along the bonded length and in turn increases the bond capacity. This result is similar to that reported in previous study by the author (Wu and Diab 2007) which concluded that the increase of effective bonding length due to creep of adhesive layer result in the redistribution of bond stresses along the bonded length which prevents debonding propagations along FRP-concrete interface.



(a) Specimen CFRPL2-2 (b) Specimen BFRPL1-3

Figure 6: FRP-Sheet strain distribution along the bonded length of specimens

Prediction of Bond Strength using a Proposed Bond Strength Model

Analytical models for estimation of bond strength, available in the literature, are evaluated on the basis of 351 bond tests performed in the past by Toutanji et al. (2008). It is found that the formula proposed by Chen and Teng (2001) better predicts the experimental measurements for all types of composite materials. Even though, this model fails to correctly predict bond strength of specimens in this study as the FRP sheets bonded to concrete using flexible adhesive. This model and the others give underestimating values as mentioned previously. This study confirms that the adhesive layer is able to increase the bond capacity of FRP-concrete interface. Therefore, the type of adhesive layer should be considered through all exciting models. In this study the most accurate bond strength model introduced by Chen and Teng (2001) will be modified to consider the type of adhesive layer based on the limited number of experiments available in this study. The bond strength of an FRP-concrete interface of simple shear joint based on the Chen and Teng (2001) model is represented by;

$$P_u = 0.427\,\beta_p \beta_L b_f L_e \sqrt{f_c'} \qquad (2)$$

$$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_c'}}}\,, \quad \beta_p = \sqrt{\frac{2-{b_f}/{b_c}}{1+{b_f}/{b_c}}}\,, \quad \beta_L = 1 \; if \; L \geq L_e;\; \beta_L = \sin\frac{\pi L}{2L_e} \; if \; L \leq L_e \qquad (3)$$

where E_f, t_f, b_f are modulus of elasticity, thickness and width of FRP sheets, respectively; f_c', b_c are the concrete compressive strength and width of concrete block, respectively; L_e, L are the effective bonding length and bond length, respectively.

Experimental results showed that the flexible adhesive layer increases the effective bond length which results in the redistribution of shear stresses along the bonded length and in turn increases the bond capacity of FRP-concrete interface. Therefore; a coefficient β_a is proposed to the effective bonding length and to the bond strength equations of Chen and Teng model (2001). From the regression of the limited test data available in the present study, the factor β_a is represented as

$$\beta_a = \sqrt{\frac{E_a}{2.45}} \tag{4}$$

Where E_a is the modulus of elasticity of adhesive layer in GPa.

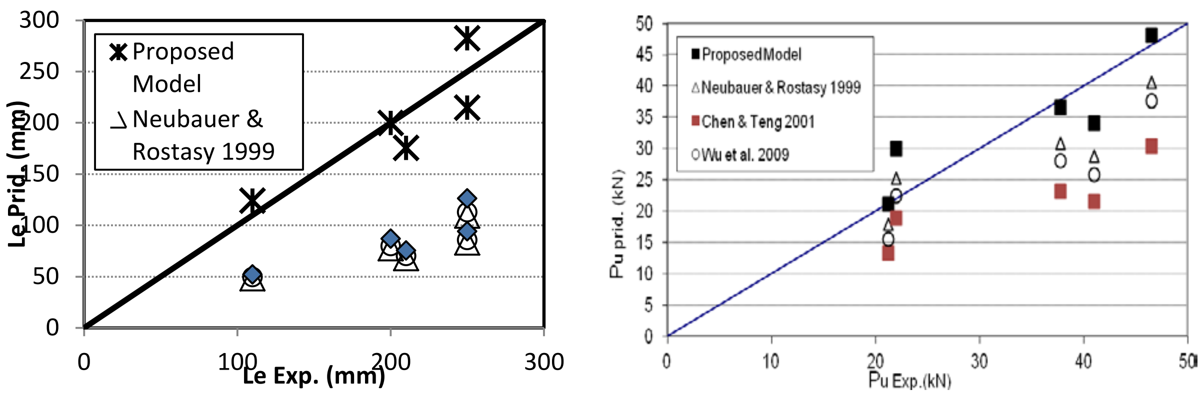
Equations (2, 3) for effective bonding length and bond strength of FRP bonded joint can be modified to include the adhesive factor, β_a, as

$$L_e = \sqrt{\frac{E_f\, t_f}{\beta_a^2 \sqrt{f_c'}}} \tag{5}$$

$$P_u = 0.427\, \beta_p \beta_L b_f L_e \sqrt{\beta_a f_c'} \tag{6}$$

Comparing the Proposed Bond Strength Model to other Existing Models

The results of the proposed model and those which were obtained from the three selected models for the specimens in the present paper are presented in Figure 7. It is clear that the proposed model predicts satisfactory the effective bonding length and the bond strength that were measured experimentally. It can be seen that the other models underestimate the bond strength and the effective bonding length. The main cause for the poor performance of these models is due to neglecting the type of adhesive.



(a) Effective Bonding Length (b) Bond Strength

Figure 7: Test versus Predicted Results

Conclusion

This study has presented an experimental program on the bond performance of FRP sheets bonded to concrete with flexible adhesive. The type of adhesive has an effect on both the effective bond length and the bond strength of FRP-concrete strengthening system. From the experiment results and the comparative studies of some analytical models for bond strength, it is noticed that the flexible adhesive layer increases both of the effective bonding length and the ultimate bond strength. Flexible adhesive layer has improved ductility of FRP-concrete interface which is crucial to improve ductility of FRP strengthened beams. Finally, the evaluation of bond strengths of the experiment results using various existing models showed that these models need to be modified to consider the type of adhesive layer. Based on the statistical analysis of a limited number of shear test results, which were devoted in this study to investigate the effect of adhesive layer on FRP-concrete interface, the Chen and Teng bond strength model(2001) has been modified taking into its consideration the type of adhesive layer.

References

Buyukozturk, O., Gunes, O., & Karaca, E. (2002). Characterization and Modeling of Debonding in RC Beams Strengthened with FRP Composites. Proceeding of the *15th ASCE Engineering Mechanics Conference,* Columbia University, New York, 1-8.

Caggiano, Antonio, Enzo Martinelli, & Ciro Faella (2012). A fully-analytical approach for modelling the response of FRP plates bonded to a brittle substrate. *International Journal of Solids and Structures* 49, 2291-2300.

Chen, J. F., & Teng, J. G. (2001). Anchorage strength models for FRP and steel plates bonded to con-crete. *Journal of structural engineering, ASCE*, 127(7), 784-791.

Dai, J.G, Ueda, T., Ito, T. (2005). Flexural strengthening of RC beams using externally bonded FRP sheets through flexible adhesive bonding. *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005)*, 205- 213.

Dai, J.G. & Ueda, T. (2003). Local Bond Stress Slip Relations for FRP Composites-concrete Interfaces. *Proceedings of FRPRCS-6*, Edited by Tan, K. H., l, 143-152.

Diab H.M., &Wu Z. (2009). Bond Behaviour of Different FRP Sheets. *Proceedings of FRPRCS-9*, Sydney, Australia, 2009.

Hamoush, SA., & Ahmad SH. (1990). Debonding of Steel Plate-StrengthenedConcrete Beams. *J Struct Eng*,116(2),356–71.

Lu, X.Z., Teng, J.G., Ye, L.P & Jiang, J.J. (2005). Bond-slip models for FRP sheets/plates bonded to concrete. *Engineering Structures*, 27(6), 920-937.

Mazzotti C., Savoia M., & Ferracuti B.(2008). An Experimental Study on Delamination of FRP Plates Bonded to Concrete. *Construction and Building Material*, 22, 1409-1421.

Mitolidis, G., Kappos, A., & Salonikios T. (2008). Bond tests of SRP and CFRP – strengthened concrete prisms. *Proceeding of the 4th International Conference on FRP Composites in Civil Engineering (CICE2008)*, Zurich, Switzerland.

Nakaba K, Kanakubo T, Yoshizawa T, & Yoshizawa H. (2001). Bond behaviour between fibre-reinforced polymer laminates and concrete. *ACI Struct. J* ,98(3),359–67.

Neubauer U, & Rostasy FS. (1997). Design aspects of concrete structures strengthened with externally bonded FRP-plates. *Proceedings of the seventh international conference on structural faults and repair*, 2. Edinburgh: ECS Publications,109-127.

Tuakta, C., & Büyüköztürk, O. (2012). Conceptual model for prediction of FRP-concrete bond strength under moisture cycles. *Journal of Composites for Construction* 15(5) , 743-756.

Wu Z, Islam SM, & Said H.(2009). A three-parameter bond strength model for FRP-concrete interface. *Journal of reinforced plastics and composites* , 28(19), 2309-2323.

Wu, Y., Zhou, Z., Yang, Q., & Chen, W. (2010). On shear bond strength of FRP-concrete structures. *Engineering Structures*, 32(3), 897-905.

Wu, Yu-Fei, Xin-Sheng Xu, Jia-Bin Sun, & Cheng Jiang. (2012). Analytical solution for the bond strength of externally bonded reinforcement. *Composite Structures* 94 (2012), 3232-3239.

Wu, Z.S., & Diab, H.M. (2007). Constitutive Model for Time-Dependent Behavior of FRP-Concrete Interface. *Journal of Composites for Construction*, *ASCE*, Vol. (11), 477-486.

Xia, S.H, & 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)*, 411-418.

Yoshizawa, H., Wu, Z. S., Yuan, H. & Kanakubo, T. (2000). Study on FRP-Concrete Interface Bond Performance. *Journal of Materials, Concrete Structures and Pavement, JSCE*, 662(V-49), 105-119.