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Analytical Studies on Bond-Slip models on FRP-Concrete Interfaces

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Abstract: The use of externally bonded fiber reinforced polymer (FRP) reinforcement to strengthen reinforced concrete (RC) structures is becoming popular due to their superior properties such as, high tensile strength, long-term durability, corrosion resistance and light weight. The major issue in FRP is bond action between fiber reinforced polymers (FRP) and reinforced concrete members which affects the performance and reliability of external strengthening systems. Hence the study mainly focuses on the behavior of the interface between FRP and concrete. The behavior is examined through finite element (FE) simulations. FE simulation models were created for the parametric study to investigate the effect of several parameters on the bond behavior between FRP and concrete surfaces. The parametric study is conducted for different concrete grades by varying width and thickness of FRP laminate. The regression analysis is carried out and the best fit is arrived for the considered parameters.

Keywords: Finite Element, FRP, reinforced concrete, bond slip, debonding, delamination, laminates, stress transfer

1. INTRODUCTION

Deterioration of concrete structures is one of the major problems in construction industry now a day. The RC structures deteriorate due to many reasons, such as corrosion of reinforcement, aging, poor design or construction, exposure to harmful environments and due to different natural disaster. As the complete reconstruction of the structures is not economical. So, strengthening or retrofitting is an effective way to strengthen the structural members.

In previous decades, bonded steel plates were used as external reinforcement for existing concrete structures. This technique is used to increase the strength of structural members. Although steel bonding technique is simple, cost effective and efficient, the serious problem is deterioration of bond at the steel and concrete interface due to corrosion of steel. The use of externally bonded fiber reinforced polymer (FRP) reinforcement to strengthen reinforced concrete (RC) structures is becoming an increasingly popular retrofit technique. Due to its better features such as high tensile strength, long-term durability, corrosion/fire resistance, and low weight, fiber-reinforced polymer (FRP) plates have been extensively employed to replace steel plates in recent years; FRPs have almost completely replaced steel plates as externally epoxy-bonded reinforcement for concrete.

As flexural reinforcement, FRP-plate significantly in- crease the stiffness and load capacity of concrete beams, but decrease their ductility and often result in brittle failure modes which are not desirable in structural design. Thus, the most frequent and studied type of failure is the delamination of FRP plate and the adjacent concrete cover due to the normal and concentration of shear stress at the end of the bonded plate.

FRP composite materials are comprised of high strength continuous fibers, such as glass, carbon, or steel wires, embedded in a polymer matrix. The fibers provide the main reinforcing elements while the polymer matrix (epoxy resins) acts as a binder, protects the fibers, and transfers loads to and between the fibers. FRP composites can be manufactured on site using the wet lay-up process in which a dry fabric, made of car- bon or glass, is impregnated with epoxy and bonded to prepared concrete substrate. Once cured, the FRP becomes an integral part of the structural element, acting as an externally bonded reinforcing system.

A large number of experimental and analytical re- search has been conducted on the behavior of FRP to concrete interfaces. Debonding failures in FRP- strengthened RC structures are largely controlled by the behavior of the interface between the FRP and the con- Crete. As a result, a thorough understanding of the behavior of FRP to concrete interfaces is required for the safe and cost-effective design of externally bonded FRP systems.

In particular a reliable bond–slip model for the inter- face is of fundamental importance to the accurate modeling and hence understanding of debonding failures in FRP-strengthened RC structures. For the FRP–concrete contact, Ueda and Dai (2004) studied a local bond stress–slip model (shear bond model). The shear bond model was developed using a FRP stress–slip relation- ship at the loaded end of a pullout bond test, which simplified the necessary measurements and reduced data dispersion. Only two material constants are required in the shear bond model: interfacial fracture energy and interfacial ductility factor. To represent instances with short bond lengths, the shear bond model was expanded to become a bond stress–slip– FRP strain model. The mechanical characteristics of FRP, adhesive materials, and the concrete substrate are all considered in both the original and extended shear bond models. In addition to the shear bond model, the formulas for interfacial fracture energy, effective bond length, and bond strength for a given anchorage length are given.

Teng et al. (2000) found that in the modelling of FRP- strengthened RC structures, a correct local bond–slip model is critical. A survey of existing bond strength and bond–slip models is given in this study. The results of 253 pull tests on basic FRP-to-concrete bonded connections are then used to evaluate these models, resulting to the conclusion that a more accurate model is necessary. The paper proposes a set of three novel bond–slip models with varying levels of intricacy. The new bond–slip models are based on the predictions of a meso-scale finite element model, with appropriate adjustments to match their predictions with the experimental results. This work is unique in that the new bond–slip models are not based on axial strain measurements on the FRP plate; instead, they are based on the predictions of a meso-scale finite element model, with appropriate adjustments to match their predictions with the experimental results.

Esfahani et al. (2007) Estani investigates the flexural behavior of reinforced concrete beams reinforced with Carbon Fibre Reinforced Polymers (CFRP) sheets at different reinforcing bar ratios. Three different reinforcing ratios (30%, 60% and 80% of the tensile reinforcement balanced ratio) were considered in this study. CFRP sheets were used to reinforce nine of the twelve casted specimens in flexure. CFRP sheets vary in width, length, and number of layers in various specimens. In comparison to the control specimens, the reinforced beams' flexural strength and stiffness increased. Beams were made to fail in flexure. The failure mode of each beam is noted. Increasing the number of layers CFRP sheet significantly changes the stiffness of the beam only after the yielding of tensile reinforcement Addition of FRP layers before yielding of tensile reinforcement does not increase the stiffness of the control beam because the ratio of axial stiffness of FRP layer to the axial stiffness of tensile reinforcement is small. By increasing reinforcing ratio, the effect of increase in FRP layers on the rate of increase in the ultimate load capacity of the beams decreases. Higher performance of strengthening with FRP sheets can be achieved for beams of lower reinforcing bar ratio with reinforcing bar ratio close to the maximum reinforcement ratio, failure of the strengthened beams occurs by either FRP rupture or concrete cover delamination with adequate ductility.

Neubauer and Rostasy (1997) investigated the design aspects of concrete structures strengthened with externally bonded CFRP-plates. Ferracuti (2006) conducted experimental analyses and numerical modelling of strengthening of RC structures by FRP. Teng et al. (2006) investigated the FRP-to concrete interfaces between two adjacent cracks and suggested a theoretical model for debonding failure. Lu et al. (2005) suggested a new bond-slip models for FRP sheets/plates bonded to concrete.

Debonding Failure Modes

A great amount of research has been carried out in recent years on the behavior and strength of these FRP-strengthened RC beams. The researchers have identified a number of failure modes. A schematic representation of the six main failure modes observed in tests are termed as (a) flexural failure by FRP rupture, (b) flexural failure by crushing of compressive concrete (c) shear failure, (d) concrete cover separation, (e) plate end interfacial debonding, and (f) intermediate crack induced interfacial debonding. Among the six failure modes, the first three are not totally different from those in conventional RC beams, although there are some important differences (Teng et al. (2000)). The three failure modes shown below are not found in conventional RC beams and are instead modes unique to beams bonded with a soffit plate.

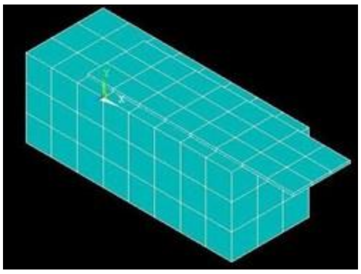


Figure 1: Specimen

The three modes of debonding failures (d)–(f) can be broadly classified into two types (Teng et al. (2000)): (a) those that initiate at or near one of the plate ends (simply referred to as the plate end hereafter) and then propagate away from the plate end; and (b) those that initiate at an intermediate flexural or flexural-shear crack and then propagate from such a crack towards the plate end. The first type of debonding is referred to as plate end debonding and the second is referred to as intermediate crack induced interfacial debonding. Of these two failure modes, plate end debonding is by far the more commonly reported failure mode. Although less commonly reported, failures by intermediate crack induced debonding are likely to control the strength of a significant portion of FRP strengthened beams.

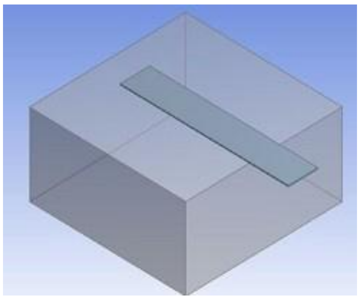
Finite Element Model

In this study, a 3D nonlinear finite element model is developed using ANSYS 19.0 to simulate a concrete prism with an attached GFRP laminate as in the single shear test. The effect of different breadths of GFRP laminate, taken as 50 mm, and 75 mm of the total width of the prism, as well as different thickness 2 mm,3 mm4 mm,5 mm and 6 mm are studied and compared.

The concrete prism is of size 150 mm x 150 mm x150mm. The bond length of FRP is 300 mm. In order to study the effect of varying width and thickness of FRP laminate along with different concrete grades M25, M30, M35, adhesive development lengths on the normal and shear stress distribution, were modelled, as shown in Fig. 1. The free end of the FRP laminate (unattached) had a length of 100 mm for the entire developed models.

The concrete and FRP materials were modelled using SOLID 185 and TARGE170 elements respectively. SOLID 185 is a 3D element defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The level of mesh refinement in the vicinity of the GFRP - concrete interface is finer than the rest of the developed models, as shown in Fig.2. In addition, an interface element CONTA174 is a 3D zero thickness element defined by an eight-node linear interface element that simulates an interface between two surfaces and the subsequent de- lamination process, where the separation is represented by an increasing displacement between nodes within the interface element itself. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The cohesive zone elements are placed between continuum elements and do not represent any physical material but rather describe the cohesive forces (traction), which occur when material elements are being pulled apart.

Figure 2: Finite Element Model



2. RESULTS AND DISCUSSION

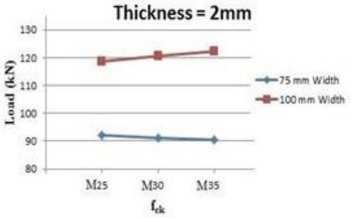
1.1. *Load vs. Thickness plots for various concrete grades*

The load under different thickness of FRP laminate isplotted for concrete grades M25, M30, M35 considering two different width of laminate 75 mm and 100 mm which is shown in Figure 3.

It is found that the concrete grade M35 with FRP width 100 mm is capable of carrying the highest load compared with the other two grades. Also, the M25 grade with both 75 mm and 100 mm width of FRP carries the lowest load compared with the other two grades. The results are shown in Fig. 3.

1.2. *Load vs. Thickness plots for various widths*

The load for different thickness of FRP laminate is plotted. The behavior is compared between two different widths of FRP for different grades of concrete M25, M30, M35. As the thickness increases, the load decreases but at 5 mm the load suddenly increased. The FRP width 100 mm carries the highest load compared to width 75 mm. The results are shown in Fig. 4.



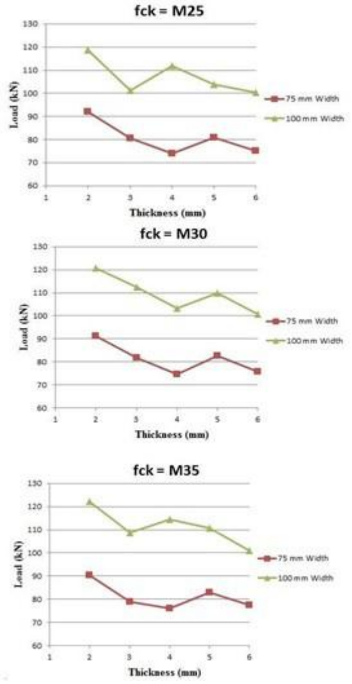


Figure 3: Load vs. Thickness plots for various concrete grade

Figure 4: Load vs. Thickness plots for various widths

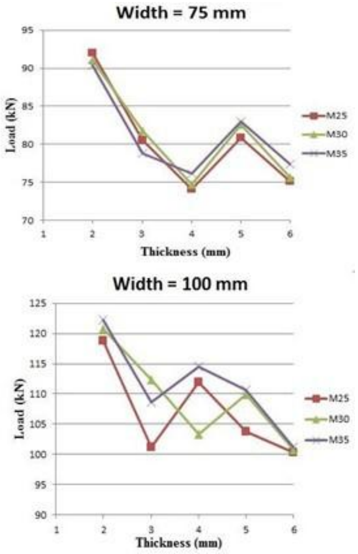


Figure 5: Load vs. fck plots for thickness 2mm

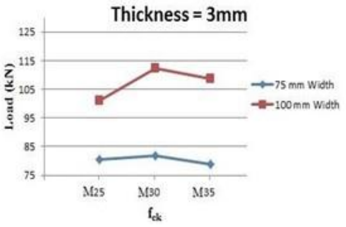


Figure 6: Load vs. fck plots for thickness 3mm

1.3. *Load vs. fck plots for various thickness*

The load for different concrete grades for different FRP width is plotted. The behavior is compared for different thickness is shown in Figure 5-9. As the compressive strength increases, the load carrying capacity increases. Also, it is seen that the FRP thickness 2 mm with concrete grade M35 carries the highest load compared to other grades.

1.4. *Statistical Analysis*

A Nonlinear regression analysis is carried out. In this analysis, a regression curve was fitted into the data relating the maximum force. As a result of this analysis, the following mathematical relation between the above mentioned quantities was found.

$$P = D f_{ck}^{A} b^{B} t^{c} \qquad (1)$$

Regression analysis results are shown in Table 1. ANOVA analysis is carried out to find the Residual squared which is shown in Table 2.

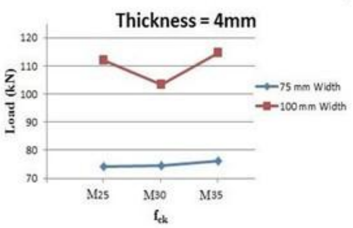


Figure 7: Load vs. fck plots for thickness 4mm

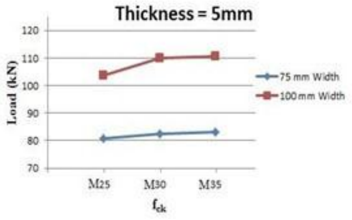


Figure 8: Load vs. fck plots for thickness 5mm

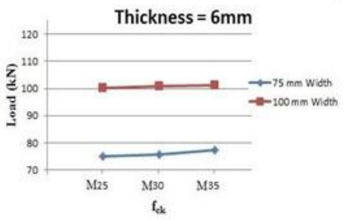


Figure 9: Load vs. fck plots for thickness 6mm

Table 1: Parameter Estimates

Parameter	**Estimate**	**Std. Error**	**95% Confidence**	
			Lower Bound	**Upper Bound**
A	0.082	0.059	-0.039	0.203
B	1.045	0.059	0.925	1.166
C	-0.137	0.02	-0.179	-0.095
D	0.804	0.267	0.255	1.353

Table 2: ANOVA

Source	**Sum of Squares**	**df**	**Mean Squares**
Regression	278504	4	69626.124
Residual	471.871	26	18.149
Uncorrected Total	278976	30	
Corrected Total	7346.63	29	

3. CONCLUSION

The variation of the different parameters for the bondslip model has been investigated using the ANSYS 19. The analysis is carried out considering the Bilinear bond slip model. The parametric study was made with different widths, thickness and grade of concrete. The following conclusions were made from the parametric study,

1. Considering the variation in thickness of FRP, the maximum load carrying capacity reduces when the thickness increases up to 4 mm in all specimens and above 4 mm, the load becomes constant.
2. As the width increases, the load carrying capacity increases. For the same thickness of 4 mm, the load carrying capacity of 100 mm width of FRP is 39 % higher than 75 mm width of FRP.
3. Among the three parameters, grade of concrete has least effect in increasing the load carrying capacity. Generally, the insignificant in load carrying capacity of FRP.
4. From the nonlinear regression analysis, the Corrected sum of squares value is 0.936 which is the best fit for the considered parameters.

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