論文 Shear Adhesion Behavior of Concrete-epoxy-steel and Concrete-epoxy-CFRP Interfaces

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ABSTRACT: Experiments were performed to study the shear adhesion behavior of concrete-epoxy-steel/CFRP interfaces. The average shear strength of interface is found between 1.1 to 3.3 MPa. The thin layer of adhesive results the most effective bonding. The average shear stress at failure decreases with plate thickness for steel plate bonding. The longer bond length decreases the average shear strength but increases the ultimate shearing force. Shear strength of the interface also increases with concrete strength. The major failure mode is debonding of concrete-epoxy joint in steel plate bonding whereas for CFRP bonded specimens, it is shearing-off of concrete below CFRP layer.

KEYWORDS: adhesion, average shear stress, bond strength, CFRP, concrete, epoxy adhesive, interface, plate bonding, shear stiffness, shear strength, steel plate

1. INTRODUCTION

Plate bonding technique using epoxy and steel plates or Carbon Fiber Reinforced Plastics (hereafter CFRP) sheets, has emerged as one of the effective methods for strengthening and retrofitting existing concrete structures. Debonding failure in plate bonded structure is one of the catastrophic failures, which depends on the stress conditions in bonded joint. The mechanical action of steel or CFRP with concrete in epoxy joint is mainly by shearing. Thus, shear adhesion behavior of interface between concrete and the strengthening material is very important to clarify the debonding phenomenon in such structures. Studies regarding bond between steel or CFRP and concrete in epoxy joint have been done in the past[1-5]. However, the parameters which affect the bond behavior have not been addressed collectively. Moreover, there have been very few comparative studies between steel and CFRP bonded specimens. The objectives of this study are to enhance the understanding of shear adhesion behavior of concrete-epoxy-steel and concrete-epoxy-CFRP interfaces as affected by various parameters and to compare the various failure modes in both types of bonding.

In this study, sixteen reinforced concrete prisms bonded with steel plates and CFRP sheets were tested. Concrete strength, thickness of the strengthening material, adhesive thickness and bond length were taken as variables. Ultimate shearing force, average shear strength of the joint, maximum shear stress at failure, strain distribution in strengthening material and failure mode of the specimen were investigated.

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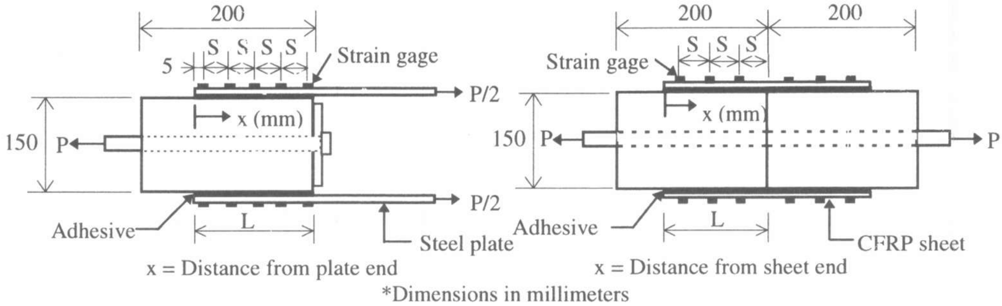
2. OUTLINE OF EXPERIMENTS

The details of test specimens bonded with steel plates and CFRP sheets are shown in **Fig. 1.**



a. For steel plate bonding **b. For CFRP sheet bonding**

Fig. 1. Test setup for specimens

Two 100 mm wide steel plates were bonded with epoxy resin on the opposite sides of a reinforced concrete prism of size 150 mm x 150 mm x 200 mm. Before bonding, steel plates and concrete surfaces were mechanically abraded and thoroughly cleaned with acetone. For these specimens, primer was not used and epoxy was directly applied on concrete surface. The thickness of steel plate and adhesive layer were varied from 2.3 mm to 6.0 mm and 2.0 mm to 6.0 mm respectively. Adhesive thickness was controlled with the help of 1.0 mm thick brass washers. Three different bond lengths 50 mm, 100 mm and 150 mm were used. The prism was clamped using an unbonded prestressing bar of 19.3 mm dia., which was fitted with a steel plate of dimension 120 mm x 120 mm x 25 mm at the end. **Table 1** shows the mechanical properties of steel plates used in the tests.

Table 1. Mechanical properties of steel plate

Plate thk. (mm)	Yield strength (MPa)	Modulus of elasticity (GPa)
2.3	378	209
4.5	382	198
6.0	398	210

Table 2. Properties of CFRP tow sheets

Property	Type 1 (FTS-C1-30)	Type 2 (FTS-C1-20)
Fiber amount (gm/m^2)	300	200
Thickness of sheet (mm)	0.167	0.111
Tensile strength(MPa)	3400	3400
Tensile stiffness(N/mm)	38400	25500
Modulus of elasticity(GPa)	230	230
Max. elong. at failure(%)	1.5	1.5

Table 3. Properties of the epoxy adhesives

Property	For steel bonding	For CFRP bonding
Pot life (minutes)	50	35
Compressive strength (MPa)	72	34
Tensile shear strength(MPa)	16.6	9.8
Adherence strength(MPa)	-	1.9-2.0

For CFRP bonded specimens, two 100 mm wide unidirectional sheets were bonded on the opposite sides of two concrete prisms 150 mm x 150 mm x 200 mm in size. The CFRP sheets were applied to concrete surface with an epoxy resin that served both as adhesive and the matrix, after applying the epoxy primer. The bonding faces of concrete prisms were roughened and cleaned thoroughly beforehand. Prisms were clamped by bonded deformed re-bar of 25 mm dia., which had full embedment in concrete (embeddment length = 200 mm). **Table 2** shows the material properties of two types of sheets and **Table 3** shows the properties of two types of epoxy adhesives used in the tests. Strains in steel plates and CFRP sheets in the direction of applied force were recorded during the test.

3. RESULTS AND DISCUSSION

3.1 SPECIMENS BONDED WITH STEEL PLATES

Test results for concrete specimens bonded with steel plates are shown in **Table 4.** All the specimens except ST-2 and ST-4, failed by debonding at concrete-epoxy interface, there was no cracking of epoxy itself and no debonding at the steel-epoxy interface. This illustrates that the weakest plane in such joint lies between the adhesive and concrete. Specimens ST-2 and ST-4 failed by concrete splitting at the plate cutoff zone. Obviously, the maximum concrete stress occurs at the plate cutoff point, once this stress exceeds the concrete surface tensile strength, splitting occurs. Effects of concrete strength, plate thickness and adhesive thickness on average shear strength of concrete-epoxy-steel interface are shown in **Fig. 2** to **Fig. 4** respectively. It is seen that the average shear strength of the interface increases with the concrete strength. It is also observed that the smallest plate and adhesive thickness give interface the highest average shear strength.

Table 4. Results for specimens bonded with steel plates

Spe. no.	fc' (MPa)	Plate thk. (mm)	Bond length (mm)	Adhesive thk. (mm)	Ult. failure load P (kN)	Av. shear stress at failure (MPa)	Max. shear stress at failure (MPa)
ST-1	53.0	2.3	100	4	54.0	2.7	5.4
ST-2	53.0	4.5	50	2	32.5	3.3	4.4
ST-3	53.0	4.5	100	2	39.0	1.9	8.3
ST-4	35.0	4.5	50	2	25.6	2.6	5.8
ST-5	55.7	4.5	50	4	14.0	1.4	9.7
ST-6	55.7	4.5	100	4	40.2	2.0	4.2
ST-7	55.7	6.0	50	2	30.5	3.0	9.2
ST-8	55.7	6.0	100	6	30.7	1.5	9.2
ST-9	49.6	6.0	150	4	51.0	1.7	5.0

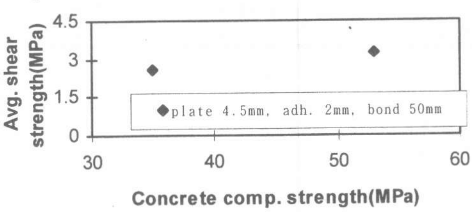


Fig. 2. Concrete strength vs. av. shear strength

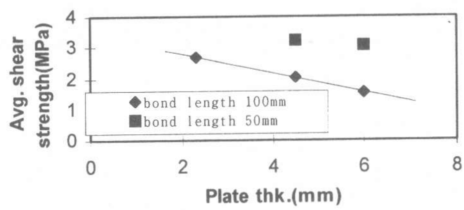


Fig. 3. Plate thickness vs. av. shear strength

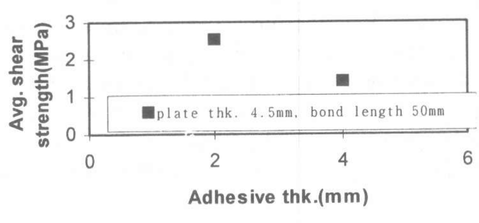


Fig. 4. Adhesive thk. vs. av. shear strength

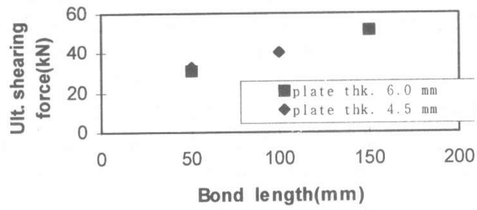


Fig. 5. Bond length vs. ultimate shearing force

Fig. 5 and **Fig. 6** show the ultimate shearing force and average shear strength for the interface versus bond length respectively. It is found that the ultimate shearing force increases with longer bond length, whereas the average shear stress decreases. This implies that, for specimens with longer bond length, some portion of bond takes nominal part in force transfer before the failure of highly stressed end. Once the first debonding occurs, stress at that point decreases and the location of maximum stress shifts towards the other end. In this way a progressive debonding occurs. The high concentration of shear stress near the loaded end of steel plate can be confirmed by the plate strain distribution for typical specimen ST-6 shown in **Fig. 7.**

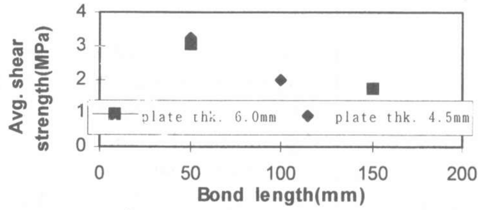


Fig. 6. Bond length vs. av. shear strength

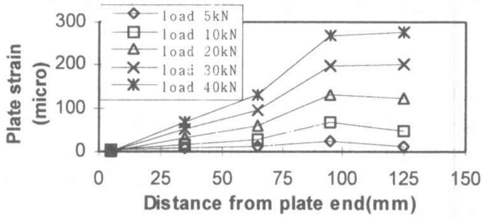


Fig. 7. Strain distribution in steel plate for ST-6

3.2 SPECIMENS BONDED WITH CFRP SHEETS

Test results for CFRP bonded specimens are shown in **Table 5.** Specimens CF-3 and CF-7 failed by detachment of CFRP from concrete, whereas CFRP rupture was accompanied in the specimens CF-6. Rest specimens showed concrete splitting along with either CFRP detachment or CFRP rupture. The detached CFRP retained some chunks of concrete on their surface. This suggests that the actual failure is somewhat shearing-off of concrete just below the CFRP sheets. Thus the concrete surface tensile strength is one of the most important factors in CFRP strengthened specimens. Brosens and Van Gemert[2], have related the debonding failure of CFRP strengthened structures to pull-off strength of concrete surface. The average shear stresses at failure were not so different, however maximum stresses were lower than in the case of steel plate bonded specimens.

Table 5. Results for specimens bonded with CFRP sheets

Spe. no.	fc' (MPa)	ft (MPa)	CFRP type/layer	Bond length (mm)	Ult. failure load P (kN)	Av. shear stress at failure (MPa)	Max. shear stress at failure (MPa)
CF-1	24.0	2.1	1 / 1	100	44.0	2.2	5.0
CF-2	24.8	2.1	1 / 1	100	40.2	2.0	2.0
CF-3	33.1	1.8	1 / 1	150	40.9	1.4	4.3
CF-4	33.1	1.8	1 / 2	100	51.8	2.6	3.6
CF-5	32.7	2.6	2 / 2	100	56.5	2.8	6.3
CF-6	36.5	4.3	2 / 1	150	33.5	1.1	3.6
CF-7	29.7	4.0	2 / 2	100	49.2	2.5	5.6

Effects of concrete strength and bond length on average shear strength of concrete-epoxy-CFRP interface are shown in **Fig. 8** and **Fig. 9** respectively. Relationship between ultimate shearing force and bond length is shown in **Fig. 10.** It is seen that, the average shear strength of interface increases with concrete strength but decreases with longer bond length. The ultimate shearing force remains somewhat constant with bond length. This suggests that the effective bond length of CFRP sheet falls somewhere below 100 mm, similar result has been reported by Chajes, and et al.[3]. The strain distribution along the CFRP sheet in the direction of applied force at various load levels for typical specimen CF-1 is shown in **Fig. 11.**

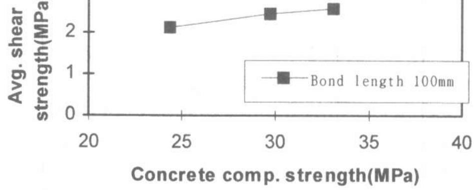


Fig. 8. Concrete strength vs. av. shear strength

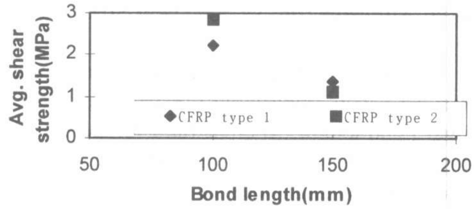
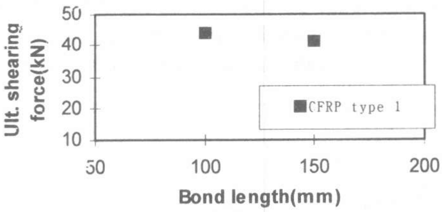


Fig. 9. Bond length vs. av. shear strength



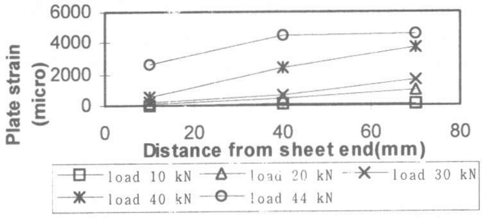


Fig. 10. Bond length vs. ultimate shearing force **Fig. 11. Strain distribution in CFRP for CF-1**

4. SHEAR STRESS IN BONDED INTERFACE

The distribution of shear stress along the bonded interface as shown in **Fig. 1**, can be computed based on the differential equation of sliding bond as given by eq. 1[4]. Assuming homogeneous isotropic linear elastic behavior for the adherents, and further assuming a linear bond slip relation for the interface, solution of eq. 1 with appropriate boundary conditions at two ends of bond line, can be written as eq. 2.

$$\frac{d^2\delta(x)}{dx^2} - \frac{\lambda}{E_P t_P}\tau(x) = 0 \qquad (1)$$

$$\tau(x) = \frac{KP}{2\beta}\left\{\left(\frac{Cosh\,\beta x}{Sinh\,\beta l}\right)\left(\frac{1}{A_p E_p} + \frac{e^{\beta l}}{A_c E_c}\right) - \frac{e^{\beta x}}{A_c E_c}\right\} \qquad (2)$$

where $\beta = \sqrt{\frac{K\lambda}{E_P t_P}}$, and $\lambda = (1 + n\rho)$, $n = \frac{E_p}{E_c}$, $\rho = \frac{A_P}{A_c}$

In above equations, $\delta(x)$ and $\tau(x)$ are local slip and local shear stress at the interface respectively. K is shear stiffness of interface, A_P, E_P and A_c, E_c are area and elastic modulus of plate and concrete respectively. P is force, l is bond length and t_p is the thickness of plate.

Fig. 12 shows the shear stresses at the interface computed from eq. 2 and from the test at distance 20 mm from plate end for specimen ST-3 at various load levels. **Fig. 13** shows the analytical shear stress distribution at load level 5 kN along the bonded interface for the same specimen. In the analysis, shear modulus of 120 MPa was used[5], the shear modulus divided by thickness of adhesive gives the shear stiffness of the interface. The elastic modulus of concrete was taken as 27.5 GPa as measured from the test. The experimental shear stress is calculated using eq. 3.

$$\tau(x) = E_p t_P \frac{\Delta\varepsilon}{\Delta x} \qquad (3)$$

where $\frac{\Delta\varepsilon}{\Delta x}$ is the strain gradient between two consecutive strain gages in plate.

It is seen that at low load levels, the analytical values agree quite well to the test values, however, near the ultimate load analytical values are found to be lower than test values. The discrepancy might be attributed to uncertainity in the the exact value of shear stiffness and the nonlinear behavior of the materials near the ultimate load. **Fig. 13** shows that, the maximum shear stress occurs at the end of plate near the load and decreases towards the other end. However, the effect of stress concentration can be observed from little higher value of stress at the plate end(x = 0).

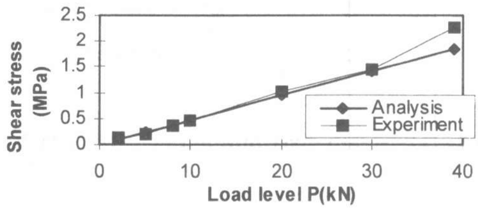


Fig. 12. Shear stress at x =20 mm for ST-3

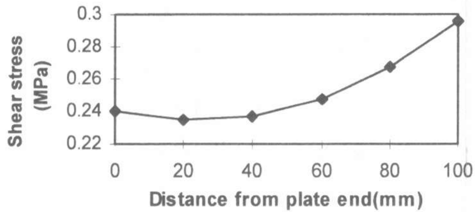


Fig. 13. Shear stress distribution ST-3(P=5 kN)

5. CONCLUSIONS

From the results presented in this paper, the following conclusions can be drawn.

The average shear strength is found in the range of 1.4-3.3 MPa for concrete-epoxy-steel interface and 1.1-2.8 MPa for the concrete-epoxy-CFRP interface respectively. However, the strain distribution is not uniform along the bonded length. The highest shear stress occurs at the end of plate or sheet near the applied force where the first debonding starts and progresses towards the other end. This causes the average shear strength to decrease as the bond length becomes longer. Three different failure modes were observed, debonding at concrete-epoxy interface, splitting of concrete and the combination of both for steel plate bonded specimens. CFRP bonded specimens exhibited shearing-off of concrete along with CFRP rupture. The slightly different failure modes of CFRP bonded specimens and steel plate bonded specimens might be due to somewhat different clamping schemes used. Specimens with low concrete strength and smaller adhesive thickness failed by concrete splitting or by the combined mode. The thicker the adhesive layer, the lower is the average shear strength of the joint. The average shear stress at failure also increases with concrete strength; for CFRP bonding the shearing-off of concrete mainly depends on surface tensile strength of concrete. The shear strength of the interface decreases with the increasing plate thickness in case of steel plated specimens. The equation presented can be used to predict the shear stress distribution along the interface, if proper value of shear stiffness is used in the computation, which should preferably be determined from the bond tests.

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