EXPERIMENTAL STUDY ON BOND BEHAVIOR BETWEEN CFRP PLATES AND CONCRETE UNDER COMBINATION OF FRACTURE MODE

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ABSTRACT

Diagonal tension cracks in reinforced concrete members adversely affect the performance of flexural members strengthened by externally boned fiber-reinforced polymer (FRP) materials. The interface between the CFRP plate and concrete is influenced by both shear bond and peeling for such conditions. The objective of this study is to understand bond behavior in CFRP plate and concrete systems under the combination of fracture mode (peeling and shear) by special double-face shear bond test specimen. The specimens were designed for different initial angles at the middle of the specimen to ensure that the interface acts for both shear and peeling conditions. From the test results, the bond behavior under the combination of fracture mode can be observed using special specimens. It is confirmed that the tensile load decreases as the peeling angle increases. The relationship between peeling angle and tensile load is determined to evaluate the bond strength under the combination of fracture mode. Based on the test results, a new calculation method under the combination of fracture mode is proposed. The proposed method makes good prediction of the bond strength between CFRP plate and concrete for shear-peeling fracture conditions.

KEYWORDS

Concrete, CFRP plate, double face, shear and peeling, combination fracture, bond strength

INTRODUCTION

In recently, many rehabilitation or strengthening of existing concrete structures using external attached CFRP (Carbon Fiber-Reinforced Plastic) plate have been developed to extend their service life. And in the strengthened concrete structures, the diagonal tension cracks failure may adversely affect the performance of flexural strengthened members by fiber-reinforced polymer (FRP) materials. In many past studies, which the FRP materials were considered to act in plane with the member surface, and the interface between the FRP materials and concrete was subjected to shear bond stress (called Mode II in fracture mechanics) have been investigated a lot. In the case of flexural strengthened concrete beams, however, when delamination is induced by the opening up (Mode I) of a flexural shear crack and a shear crack, a relative vertical displacement exists between the two sides of the crack as shown in Fig. 1. Hence, the bond performance of this type structure, strengthened by FRP materials, depends not only on the shear bond strength of the interface, but also on the combined effect of shear and peeling. The objective of this study is to investigate bond behavior of CFRP plate and concrete bonding system in peeling and shear fracture at interface simultaneously using special double-face shear bond specimen.

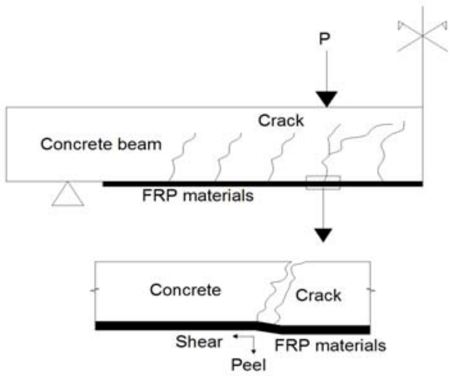

Fig.1 Combination fracture mode

EXPERIMENTAL INVESTIGATION

Specimens and CFRP Plates

Basic concept of this study is to obtain bond strength directly using double shear bond specimen. A total of 12 specimens, which have curved surface to connect two different cross sections for each specimen to allow an initial angle attached, were prepared to test by uniaxial static loading. The details of specimen are shown in Fig.2.The level difference between two different cross sections of specimen is called step height. The M24 steel bars have no connection at the middle of the specimen, and the pre-crack is introduced before loading. That means two concrete blocks just connect with CFRP plates. The specimen list is shown in Table 1. All the specimens were designed with "pre-unbond" length setting near the center region due to cause the combination of fracture failure clearly at the bonding part. The variables factors are initial angles, which designed for 2 and 4 degrees (little initial angle), 10 and 20 degrees (large initial angle), and concrete compressive strength (target strength is 13.5MPa and 21MPa). High strength type CFRP plate with 1 mm thickness is utilized in this experiment.

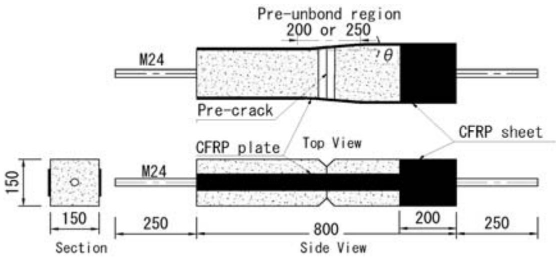

Fig.2. Specimen details (mm)

Table 1 Specimen list

Specimen	Concrete compressive strength	Concrete splitting strength	Concrete 1/3 secant modulus	Designed initial angle θ	Pre-unbond length	Step height	CFRP plate
	MPa	MPa	GPa	degree	mm	mm	
S13-2-1	18.4	1.97	20.3	2	250	8.8	High strength with 1mm thickness
S13-2-2							
S13-4-1				4		17.5	
S13-4-2							
S13-10	16.9	1.89	19.6	10	200	35.0	
S13-20				20		72.5	
S21-2-1	31.0	2.87	25.4	2	250	8.8	
S21-2-2							
S21-4-1				4		17.5	
S21-4-2							
S21-10	30.8	2.46	23.0	10	200	35.0	
S21-20				20		72.5	

Test Setup and Procedure

All the specimens were subjected to tensile force to cause shear and peeling debonding clearly at the interface of specimen. Fig.3 shows the test setup by universal testing machine. In data acquisition, for each combination of test variables, one specimen was instrumented with 8 strain gauges on the CFRP plate surface at one side. These gauges were spaced at 50 mm from the center of the CFRP plate to the load end. On the opposite side, one gauge was used at the center of the plate. In addition, the total displacements and crack widths at the specimen center were measured by using linear variable displacement transducers (LVDTs) and Pi gauges, respectively.

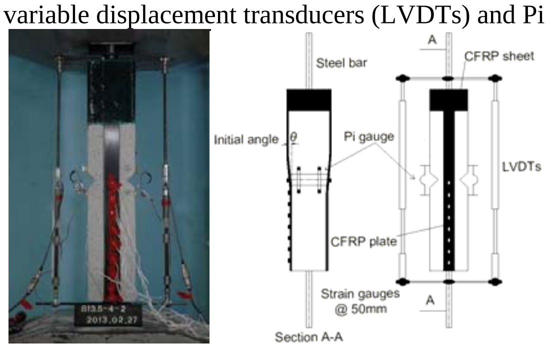

Fig.3. Test setup

RESULTS AND DISCUSSIONS

Failure Progress

The experimental results are shown in Table 2. Calculated bond strength is given by previously proposed calculating method (Matsunaga et al. 2008) for shear bond strength of CFRP plate. All the specimens were subjected to tensile force until debonding failure happened on either side. Typical failure surfaces from experimental results are shown in Fig.4. From the post-failure photographs, it is apparent that the failure surface of initial angles with 10 and 20 degrees specimens are between CFRP plate and adhesive and the initial angles with 2 and 4 degrees specimens debond in the concrete surface. It is observed that the large initial angle specimens show clearly peeling of the plate and the little initial angle specimens' debonding progress are almost controlled by shear debonding manner. Nevertheless, it is considered that all the debonding is due to the combination of fracture mode (peeling and shear).

Table 2 Experimental results

Specimen	Maximum load P (kN)	Calculated bond strength (kN)	P/P_{cal}	Failure face
S13-2-1	20.8	38.7	0.54	Concrete
S13-2-2	20.3		0.53	
S13-4-1	15.5		0.40	
S13-4-2	16.0		0.41	
S13-10	5.1		0.13	Epoxy resin
S13-20	5.5		0.14	
S21-2-1	23.4	41.4	0.61	Concrete
S21-2-2	24.3		0.63	
S21-4-1	20.8		0.54	
S21-4-2	17.0		0.44	
S21-10	7.3		0.19	Epoxy resin
S21-20	6.1		0.16	

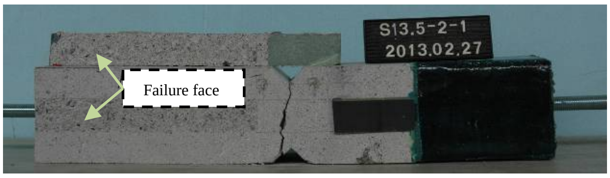

Fig.4 (a) Typical failure face of little initial angle specimen

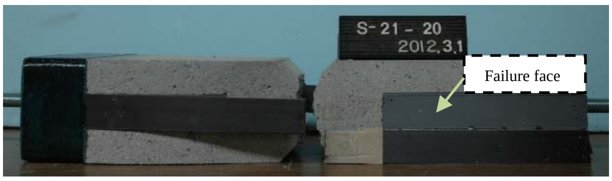

Fig.4 (b) Typical failure face of large initial angle specimen

Tensile Load vs. Displacement Relation and Strain Distributions

Some selected load-displacement curves are shown in Fig. 5. It is observed that CFRP plate peeled off toward the loaded end of the specimen with gradual increase of tensile load in the little initial angle specimens. However, in the large initial angle specimens, it can be found that as the delaminating of the CFRP plate, the 10-degree specimens and 20-degree specimens show the different behaviors. One is with a short decrease progressively after up to the maximum tensile load and gradually increased to failure. Another is up to the peak load and gradually decreased to the failure. The sudden drops in the load appeared in curves represent the propagation of delaminating of CFRP plate.

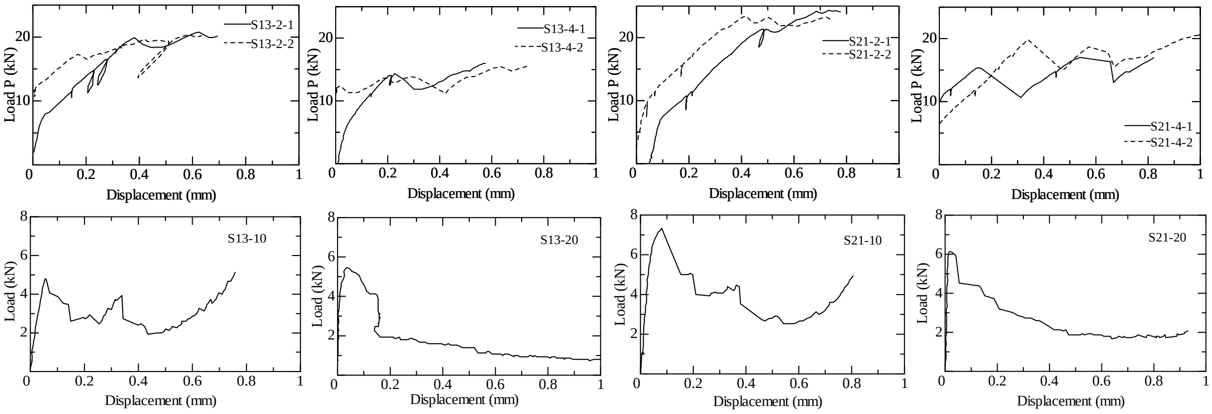

Fig.5 Load-displacement relationship

The observed strain distributions, with the tensile load versus crack width diagram for some selected specimens are shown in Fig.6. The strain distributions correspond to mark plots on the tensile load versus crack widths diagrams. As expected, some negative strains are observed due to bending of CFRP plate during debonding progress in the large initial angle specimens as same as the case of FRP sheet (Alam et al. 2012). As the debonding progress, the position of negative strain also moves to the load end. However, there is no negative strain appeared in the debonding progress of little initial angle specimens. It can be found that curves trend in little initial angle specimens are almost same to the shear bond behavior. This phenomenon supports the differences of debonding failure face shown in the previous photos.

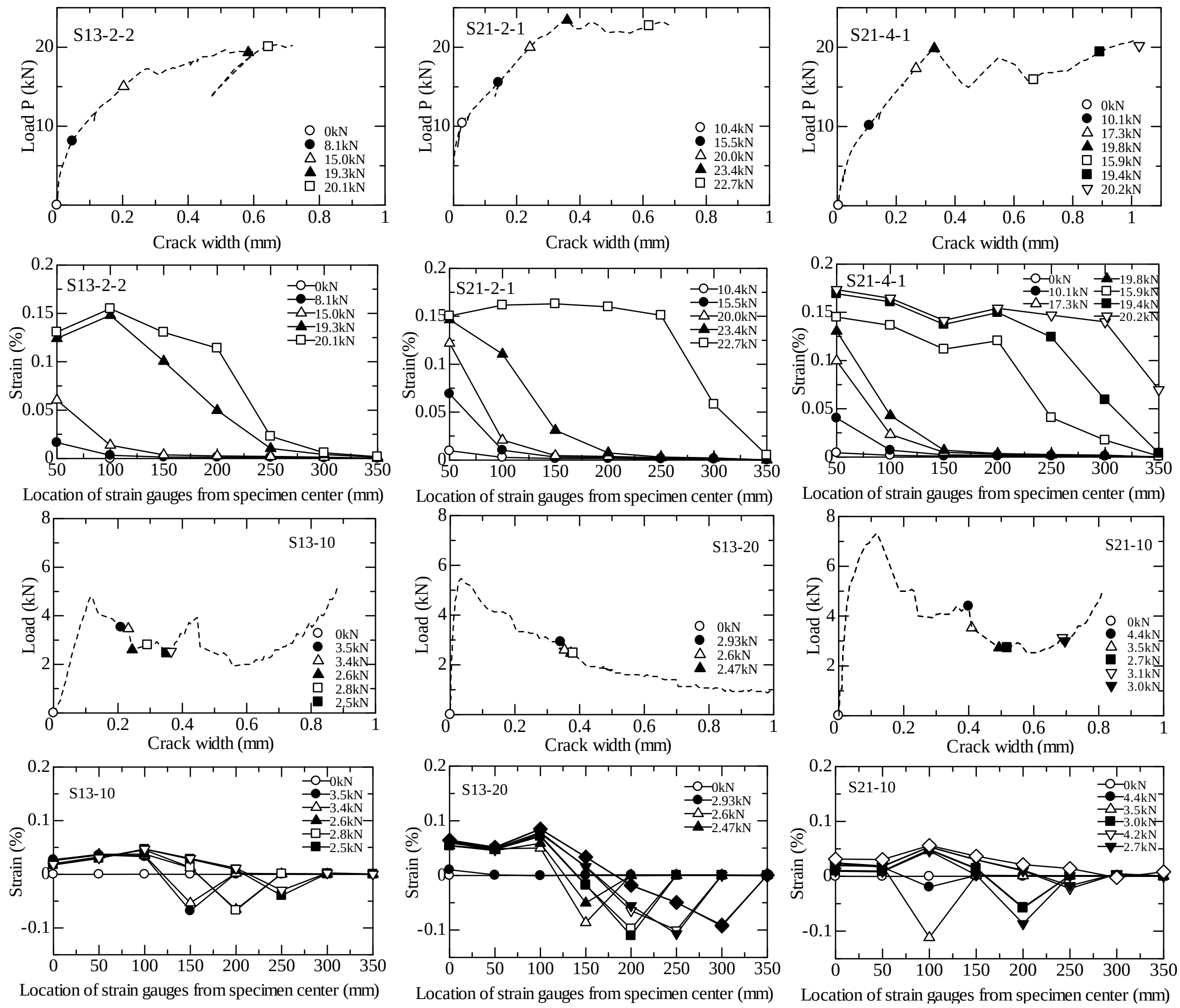

Fig.6 Strain distributions correspond to mark plots load-crack width relation

Bond Strength Evaluation

Bond strength affected by combination of fracture mode is evaluated as same method for the case of FRP sheet (Alam et al. 2012). That means it can utilize the relation of tensile load ratio (P/P_{cal}) and peeling angle ($\tan\theta$) to evaluate the combination of fracture bond strength. A detailed delamination process is shown in Fig. 7. As the load increases, the delamination of the plate occurs due to the peeling effect. Simultaneously, the bond length and the peeling angle ($\tan\theta$) between the CFRP plate and the concrete face decreases. The delaminated region is defined as the distance from where the pre-unbond region starting on test part of the specimen to the strain gauges where the minimum strain (negative strain) is observed in case of large initial angle specimens. The rest of the CFRP plate length is the bonded region, which gradually diminishes to failure. The peeling angle is obtained as the angle between the axial direction and tangential line taken from the specimen surface to the position of minimum strain appeared in CFRP plate. The load P corresponding to this minimum strain was recorded from the data to fit the relation of tensile load ratio and peeling angles. In the case of little initial angle specimens, the values at sudden drop of tensile load are selected because of no recorded negative strains.

Tensile load P ratio to the calculated bond strength P_{cal} using Eq. (1)-(5) (Matsunaga et al. 2008) is plotted against the peeling angle ($\tan\theta$) as shown in Fig. 8. It can be seen that the tensile load decreases with the increases in the peeling angle. The relationship between the tensile load ratio and peeling angle can be obtained as shown in the figure.

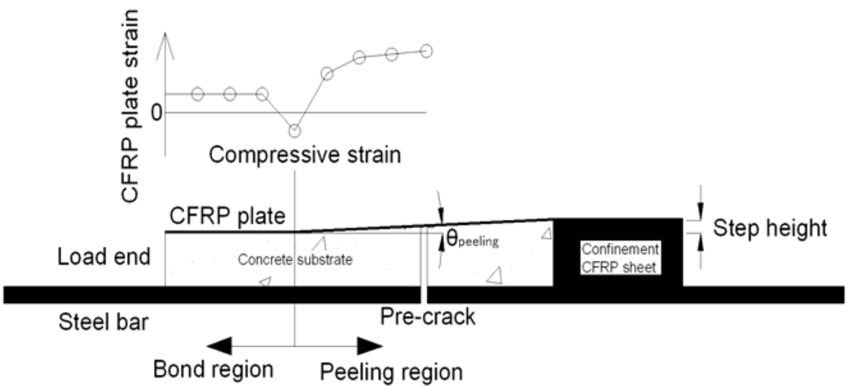

Fig.7 Details of delamination process

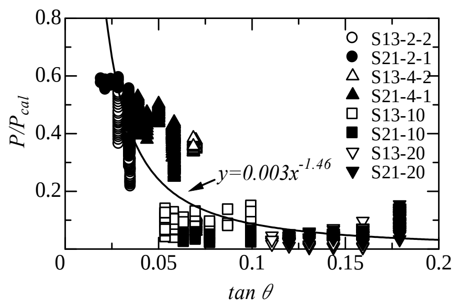

Fig.8 Effect of peeling angles on bond strength

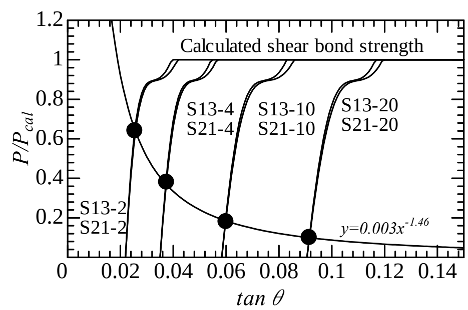

Fig.9 Evaluation of combination fracture bond strength

$$\tau_{b,\max} = 2.5 \times \sigma_B^{\ 0.23} \qquad (1)$$

$$l_e = \sqrt{\frac{2 \times t_{fp} \times E_{fp} \times s_e}{k_e \times \tau_{b.\max}}} \qquad (2)$$

$$P_b = k_e \times \tau_{b.\max} \times b_{fp} \times l_e \,(l_b > l_e) \qquad (3)$$

$$P_b = k \times \tau_{b.\max} \times b_{fp} \times l_e \,(l_b < l_e) \qquad (4)$$

$$k = \frac{1 - k_e}{2} \times \cos\left(\frac{l_b}{l_e}\right) + \frac{1 + k_e}{2} \qquad (5)$$

Where, maximum local bond stress $\tau_{b,max}$, concrete compressive strength σ_B in MPa, effective bond length l_e, width b_{fp} and thickness t_{fp} and elastic modulus E_{fp} of CFRP plate, local slippage of the effective bond area s_e (0.234mm), stress coefficient of EBSB (Equivalent Bond Stress Block) in case of effective bond length k_e (0.428), bond length l_b, bond strength P_b, stress coefficient of EBSB k (Kanakubo et al. 2003).

Plots of calculated shear bond strength varying peeling angle (is estimated by bond length) and the evaluated tensile load ratio are shown in Fig. 9. The calculated bond strength using formulas (1)-(5) is obtained with difference by bond length (l_b) to effective bond length (l_e). In this experimental investigation, it is considered that the tensile load reached the shear bond strength with all the plate delaminated. In other words, as the plate delaminated, the bond length decreased. That means the bond length is shorter than effective bond length. According to above analysis, the trend of calculated shear bond strength curves are shown in the figure. The intersection points represent the bond strength with combination of fracture mode. Therefore, using the values of $\tan\theta$ at these intersections, the corresponding values of P/P_{cal} can be calculated. The values of P/P_{cal}, $\tan\theta$ and the calculated bond length for each specimen are tabulated in Table 3. It can be seen that the predictions are better comparing of test results.

Table 3 Comparing of test results

Specimen	Calculated bond length mm	Experimental P/P_{cal}	$\tan\theta$ (cross point)	Calculated P/P_{cal}	Experimental / Calculated values
S13-2-1	61.5	0.54	0.026	0.62	0.87
S13-2-2		0.53	0.026	0.62	0.86
S13-4-1	39.5	0.40	0.038	0.36	1.13
S13-4-2		0.41	0.038	0.36	1.15
S13-10	13.9	0.13	0.060	0.18	0.71
S13-20	7.9	0.14	0.092	0.10	1.43
S21-2-1	61.5	0.61	0.026	0.62	0.99
S21-2-2		0.63	0.026	0.62	1.02
S21-4-1	39.5	0.54	0.038	0.36	1.52
S21-4-2		0.44	0.038	0.36	1.24
S21-10	13.9	0.19	0.060	0.18	1.04
S21-20	7.9	0.16	0.092	0.10	1.64

CONCLUSIONS

The bond behavior under the combination of fracture mode is observed using special specimens which have step height in surface. It is confirmed that the tensile load decreases as the peeling angle increases. The relationship between peeling angle and tensile load is determined to evaluate the bond strength under the combination of fracture mode. Based on the test results, a new calculation method under the combination of fracture mode is proposed. The proposed method makes good prediction of the bond strength between CFRP plate and concrete bonding system for shear-peeling fracture conditions.

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