Experimental Study on Interfacial Behavior of CFRP-bonded Concrete

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Abstract

Recently, the external bonding of carbon fiber reinforced polymer (CFRP) sheets has come to be regarded as a very effective method for strengthening of reinforced concrete structures. The behavior of CFRP-strengthened RC structure is mainly governed by the interfacial behavior, which represents the stress transfer and relative slip between concrete and the CFRP sheet. In this study, the effects of bonded length, width and concrete strength on the interfacial behavior are verified and a bond-slip model is proposed. The proposed bond-slip model has nonlinear ascending regions and exponential descending regions, facilitated by modifying the conventional bilinear bond-slip model. Finite element analysis results of interface element implemented with bond-slip model have shown good agreement with the experimental results performed in this study. It is found that the failure load and strain distribution predicted by finite element analysis with the proposed bond-slip are in good agreement with results of experiments.

Keywords : Carbon fiber reinforced polymer (CFRP), Structural composites, Interfacial strength, Finite element analysis (FEA), Stress transfer

I. INTRODUCTION

Recently, external bonding of Carbon fiber reinforced polymer (CFRP) plates has emerged as a popular method for the strengthening of reinforced concrete (RC) structures [1]. For the safe and economic design of externally bonded CFRP systems, a sound understanding of the behavior of CFRP-to-concrete interfaces needs to be developed. The stress state of the interface is similar to that in a pull test specimen in which a plate is bonded to a concrete prism and is subject to tension. Such pull tests can be realized in laboratories in a number of ways with some variations [2], but the results obtained are not strongly dependent on the set-up as long as the basic principle is closely represented [3].

The pull test not only delivers the failure load of the CFRP-to-concrete interface, but also has been used to determine the local bond-slip behavior of the interface [4]-[7]. This paper has two principal objectives: (a) to provide an experimental verification of the influencing factors on bond strength and (b) to present a new bond-slip model. The former part aims to clarify the effects of bonded length, width and concrete strength on bond strength, which is an inevitably important property in structural design. Related to the bond-slip model between CFRP sheet and concrete, the existing research has also led to a number of bond stress-slip models based on the direct interpretation of results from shear tests. As a fundamental constitutive law that characterizes the bond of CFRP sheet-concrete interfaces, several relationships have been proposed. (Elastoplastic model by Sato et al. [8] and Lorenzis et al. [9]; Bilinear model based on the interfacial fracture energy by Yoshizawa et al. [10]; Model based on Popovic's expression by Nakaba et al. [11]; Shear softening model by Sato et al. [12]; Three-Parameter Model for Debonding of FRP Plate from Concrete Substrate by Leung et al. [13]). These models suffer from the large scatter generally associated with such test data and also often from the lack of the consistent test variable and data available to the researchers. As a result, none of them has been found to be of sufficient accuracy when implemented to a structural design purpose. Therefore, in this study, a series of experiments were conducted and a numerical model which depicts the bond-slip behavior was proposed from the experimental results and the inverse analysis method, which is based on finite element method.

II. PULL-TEST OF CFRP PLATE BONDED TO CONCRETE

A. Experimental program

1) Experimental parameters

The experimental parameters are concrete compressive strength, bond length and bond width. The ranges of the experimental variables are shown in Table 1. Three types of concrete compressive strength (i.e., 30 MPa; 40 MPa; 50 MPa) are adopted and labeled as CS30, CS40 and CS50, respectively. Additionally, six bond lengths of CFRP, 50 mm, 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm, and three bond widths of CFRP, 10 mm, 30 mm, and 50 mm are set as the experimental variables.

2) Materials used in manufacturing specimens

The details of the concrete mix design for the different concrete compressive strengths are shown in Table 1.

The elastic modulus of high strength CFRP composite plate used in the experiment is lower than that of steel reinforcement and tensile strength of CFRP plate is much higher than that of the steel reinforcements as shown in Table 2. The fiber content of CFRP is 63.4%. The width and thickness of the CFRP plate used in the experiment are 50 mm and 1.4 mm, respectively. The material properties of the epoxy adhesive are shown in Table 3.

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Table 1. Concrete mix design

Designed compressive strength (MPa)		W/B (%)	S/a (%)	Specific weight (kgf/m^3)					
				W	C	S	G	FA	AD
CS30	30	55.4	45.6	167	256	812	999	45	1.51
CS40	40	45.1	43.2	173	326	731	991	58	2.30
CS50	50	38.7	41.8	184	426	658	959	75	3.01

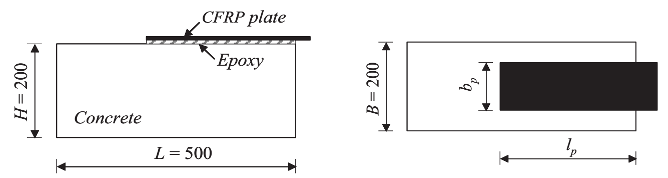
* W: Water, C: Cement, S: Sand, G: Gravel, FA: fly-ash, B: C+FA, AD: Superplasticizer (high-range water-reducing admixture)

Table 2. Material properties of CFRP plate

Elastic modulus (GPa)	Tensile strength (MPa)	Ultimate strain (%)	Fiber contents (%)
152.2	2,850.0	1.2	63.4

Table 3. Material properties of epoxy adhesive

Compressive strength (MPa)	Flexural strength (MPa)	Bonding strength (MPa)	Hardness (MPa)
80.3	42.2	3.0	84.0



(a) (b)

Fig. 1. Details of pull-test specimen (unit: mm). (a) Side view. (b) Top view.

3) Specimen details

Details of specimens are shown in Fig. 1. As shown in Fig. 1, the cross section of each specimen is 200 mm × 200 mm, and its length is 500 mm. Upon each specimen, epoxy adhesive and CFRP plate are installed with respect to the experimental variables as mentioned in section (1).

B. Test setup and data acquisition instrumentation

Loads are applied as a displacement controlled loading at an average rate of 1 mm/s by a hydraulic jack fixed to the strong frame as shown in Fig. 2. Specimens are simply supported and loaded horizontally under tensile loading. Load cell with a maximum capacity of 100 kN is equipped to measure the applied load between a hydraulic jack and zig. Loads and horizontal displacements are automatically read in and recorded by an electronic data acquisition system. Displacements are measured with linear variable differential transducers (LVDTs) installed at the edge of the specimen, and the strains on the CFRP plate are measured with strain gauges installed at the upper surface of the plate.

The strain of the CFRP plate is also measured during each loading step by attaching strain gauges to the surface of the CFRP plate. The initial crack, crack propagation, debonding and fracture between the CFRP plate and the concrete are observed visually and recorded. Also, the cracks occurring in each loading step are also recorded on the upper surface of concrete specimen.

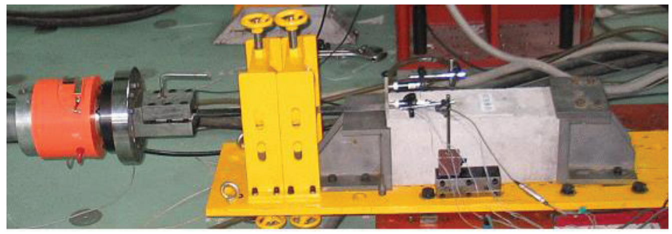
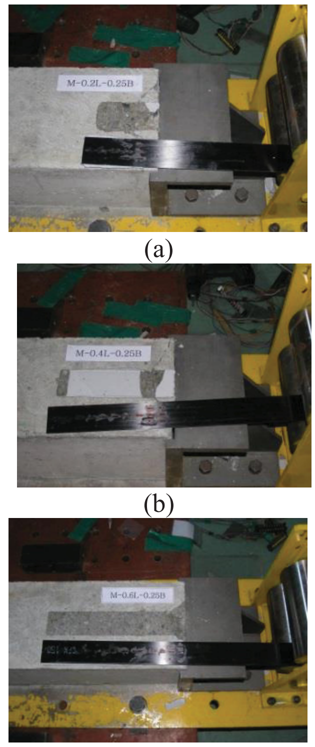


Fig. 2. Test setup for pull-test



(a) (b) (c)

Fig. 3. Failure configuration after bond failure to bond lengths. (a) Bond length 100 mm. (b) Bond length 200 mm. (c) Bond length 300 mm.

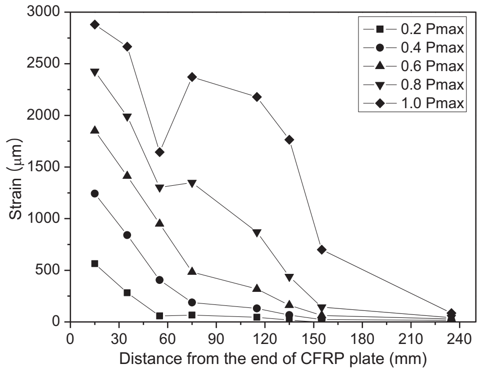
C. Experimental results and analysis

1) Failure description

As the pull-test progressed, 81% of the 108 specimens developed cracks in the concrete substrate that ran from the edge of the CFRP strip up to a point at the leading edge of the concrete block. The final failure of the CFRP-concrete bond was extremely brittle, and accompanied by a large release of energy. Some of the CFRP strips were damaged by the energy release at final failure, exhibiting splitting in the longitudinal (fiber) direction, while the epoxy of some other strips had transverse cracking post failure. Fragments of concrete were torn from the block when the strip broke free.

Increased bonded length, width, and strength parameters led to longer time-to-failure, but changes to the bonded width had the greatest impact on time-to-failure. For the shortest bonded length (50 mm), there was little warning before final failure.

While a few specimens experienced pull-out of an additional tooth of concrete at the end of the bonded length during failure, the vast majority only lost the concrete tooth at the leading edge of the bond. The remainder of the bonded region past the leading edge on the concrete block was free of epoxy after failure, and



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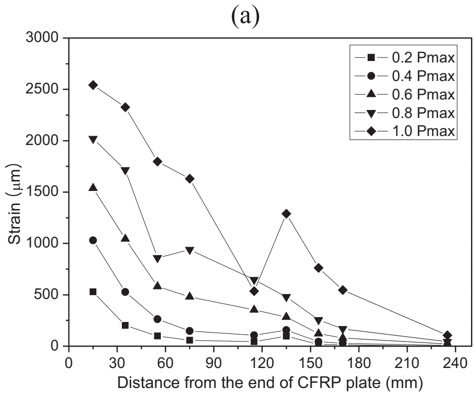

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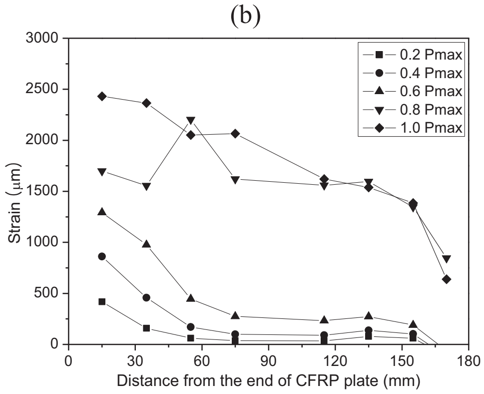


(c)

Fig. 4. Strain distribution of CFRP plate to concrete compressive strength (bond width = 50 mm). (a) Bond length 250 mm (CS30) (b) Bond length 250 mm (CS40). (c) Bond length 250 mm (CS50)

the CFRP sheets did not exhibit a significant amount of paste left clinging to the sheets as shown in Fig. 3. However, the concrete surface was rough, with numerous micro-cracks oriented in a manner indicative of the direction of bond failure progression. A pattern of regularly-spaced micro-cracks was visible throughout the bonded area, with small pieces of paste peeled back by the propagation of the bond failure.

2) Strain and bond stress of CFRP plate

Fig. 4 show that, as the load was initially applied to the specimens, the strains on the CFRP plate near the free edge of the concrete increased steadily until bond failure began. At that point, if strain redistribution was able to occur along the bonded length, the strain near the free edge of the bonded length reached a peak value and remained near that value for the remainder of the test. Meanwhile, strain began to increase at the next gauge on the bonded length, and so forth as the crack propagated until complete debonding failure occurred. Debonding failure is believed to result from a condition where the remaining bonded length is insufficient to transfer stresses between the CFRP and the concrete substrate.

As shown in Fig. 4, specimens with longer bonded length and greater width experienced the strain redistribution at higher loads. Also, strains in specimens with greater bonded width tended to be smaller in magnitude than the strains in the specimens with 10 mm of bonded width for the same load. Longer bonded length did not reduce the magnitude of strain at the location of the strain gauges, but it did ensure that strain redistribution could occur. For the bonded length shorter than 200 mm, strain redistribution did not occur to any significant degree prior to complete bond failure.

3) Effect of bond length, width and concrete compressive strength

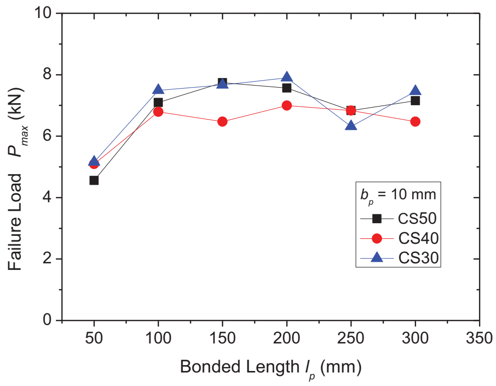
The results for the maximum load carried by the CFRP-concrete bond (P_{max}) are summarized in Figs. 5-7.

From these figures and the values obtained for P_{max}, it can be seen that concrete strength did not have a significant impact on the failure load carried by the bond for pull-test performed in this study. The fact that the compressive strength of concrete has little effect on the failure load has been also pointed out by Pan et al. [14]. Maximum loads either increased slightly by approximately 10% or decreased slightly by approximately 15% as shown in Fig. 7. There was no obvious increasing or decreasing trend. This variation can be associated with differences in specimen fabrication or inherent material variability in the concrete.

The P_{max} value displayed here for the comparisons is the average from each group of two specimens. When the bonded length changed from 50 mm to 300 mm, the failure load ratio increased by approximately 55%; beyond 200 mm bonded length, the failure load did not increase significantly, and in fact decreased by approximately 10% in some cases. This behavior is believed to be related to the fact that the bonded length may have exceeded the effective bonded length. Thus, the additional bonded length only increased the time to failure for the system. This, then, indicates that an increase in bonded length beyond the length needed to transfer stresses between the CFRP and the concrete can provide some warning time prior to the CFRP-concrete system failure. However, the extra length will not significantly impact the failure load.

Considering the average trends, increasing the bonded width had more impact on the bond failure load showing an increase of approximately 300% from 10 mm bonded width to 50 mm bonded width. Due to limitations imposed by the width of the member being repaired, increasing bonded width, while shown here to be effective at adding to the load capacity of the CFRP-concrete system, may not be practical.

Fig. 8 shows the effect of bond width on failure stress at CFRP plate. Failure stress can be related with strengthening effectiveness, which means the maximum stress level relative to the tensile strength capacity of CFRP plate. At the design stage of beam strengthened with CFRP plate, the strengthening effectiveness can be important considerations on design. From Fig. 8, it is found that failure stress decreases with bonded width of CFRP plate. This means the strengthening effectiveness decreases as bonded width increases while the failure load



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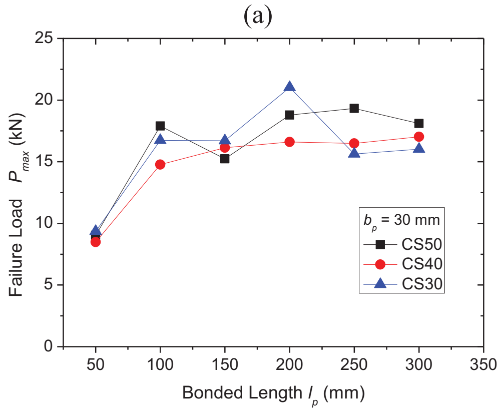

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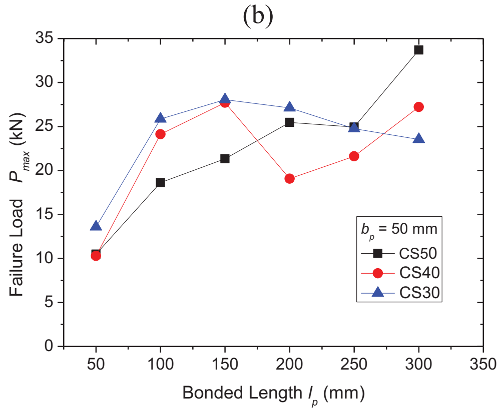

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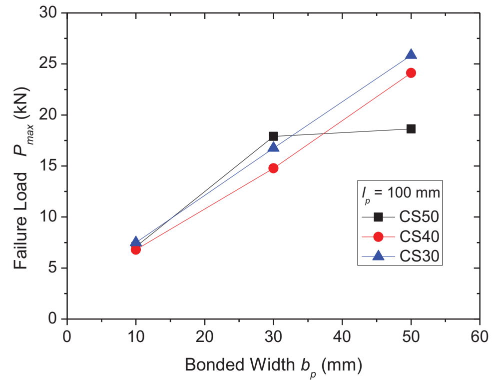
Fig. 5. Effect of bond length on failure load. (a) Bond width 10 mm. (b) Bond width 30 mm. (c) Bond width 50 mm



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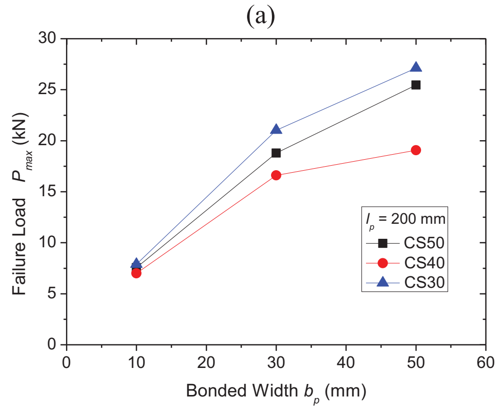

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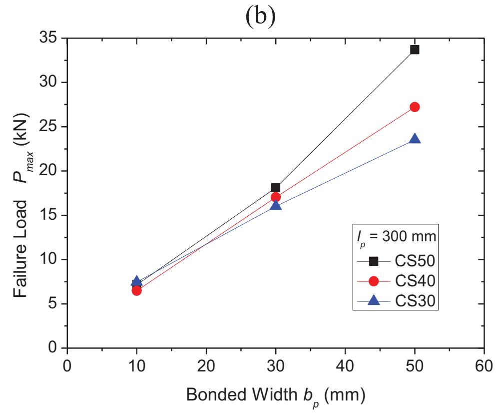


(c)

Fig. 6. Effect of bond width on failure load. (a) Bond length 100 mm. (b) Bond length 200 mm. (c) Bond length 300 mm

increases with bonded width, as shown in Fig. 6. Additionally, it is concluded that this results follow the overall trend and fall in with Chen et al.'s model [2].

III. SUGGESTION OF BOND-SLIP MODEL

A. Procedure of inverse analysis

As reported by Yuan et al. [15], the bond-slip relationship is composed of linear ascending and then linear descending parts. This study modifies the bond-slip model of Yuan et al. The proposed bond-slip model is composed of the bilinear ascending and exponential descending parts, as shown in Fig. 9, where the bilinear ascending part is separated at the points of $\delta = \alpha\delta_1$ and $\tau = \beta\tau_f$.

This separating point represents a change of the slope of the bond-slip relationship on linear-elastic behavior, which is based on the studies of Nakaba et al. [11], Savioa et al. [16], and Ueda et al. [6]. In the linear-elastic range, the bond-slip model proposed in this study evaluates interfacial shear stress as slightly higher than that of the bi-linear bond-slip model. Meanwhile, the descending part is expressed as the exponential decay function by modifying Yuan et al.'s model [15]. For this case, the model evaluates interfacial shear stress as slightly lower than that of the bilinear bond-slip model. The proposed model can consider the realistic behaviors of the CFRP-retrofit design of concrete structures. The governing equations of the bond-slip model proposed in this study are shown in Eq. (1).

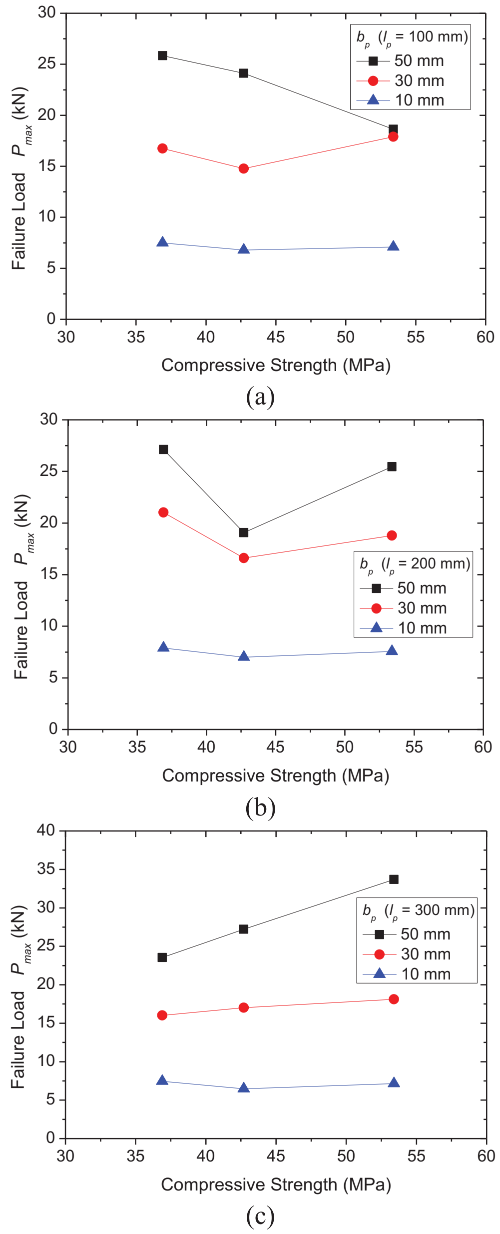


Fig. 7. Effect of concrete compressive strength on failure load. (a) Bond length 100 mm. (b) Bond length 200 mm. (c) Bond length 300 mm

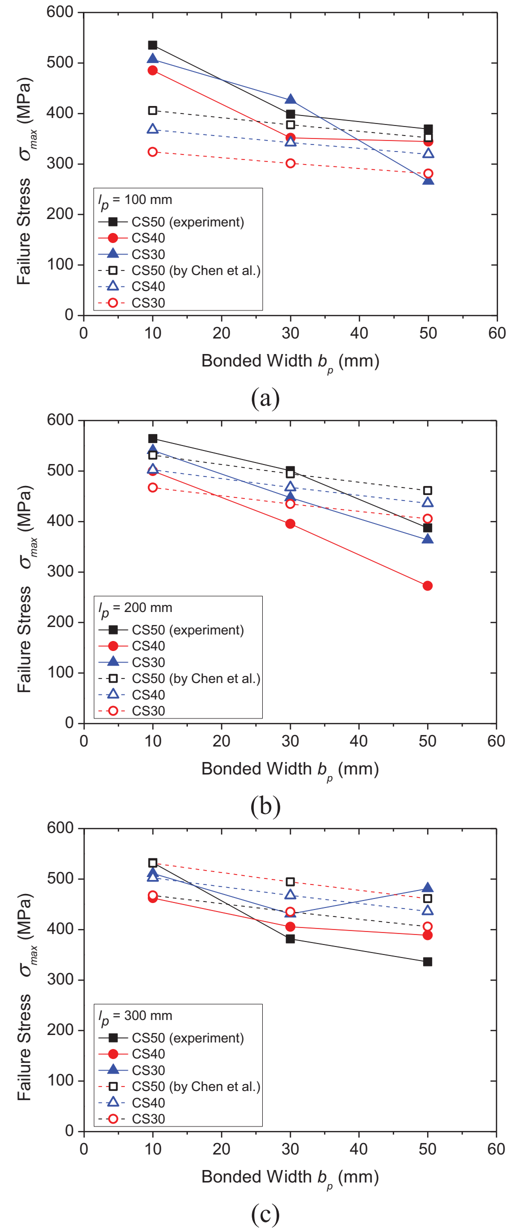


Fig. 8. Effect of bond width on failure stress at CFRP plate. (a) Bond length 100 mm. (b) Bond length 200 mm. (c) Bond length 300 mm

$$f(\delta)=\begin{cases}\beta\dfrac{\tau_f}{\alpha\delta_1}\delta, & 0\le\delta<\alpha\delta_1\\ \dfrac{\tau_f}{1-\alpha}\left[\dfrac{(1-\beta)\delta}{\delta_1}+(\beta-\alpha)\right], & \alpha\delta_1\le\delta<\delta_1\\ \tau_f e^{\frac{-\tau_f}{k}(\delta-\delta_1)}, & \delta_1\le\delta\end{cases}\qquad(1)$$

where, δ_1 is the bond slip at the maximum bond shear stress and τ_f is the maximum bond shear stress.

In order to find out five parameters τ_f, δ_1, k, α and β constituting the proposed bond-slip model, the inverse analysis is incorporated with the finite element analysis was performed. The proposed model was implemented into a 2D-finite element analytical model, as shown in Fig. 10. An interface element was used for the modeling of the bonded interface between CFRP and concrete. The relationship of the bond shear stress and the slip from the proposed model was applied to the interface element to predict the interfacial

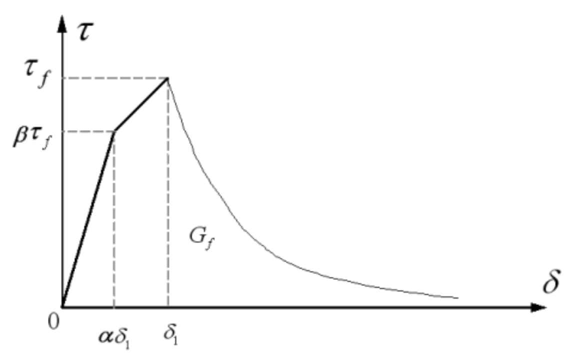


Fig. 9. Proposed bond-slip model in this study

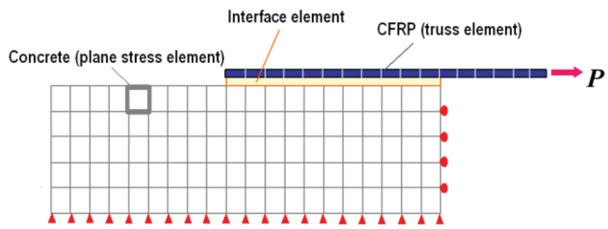


Fig. 10. 2D-finite element model

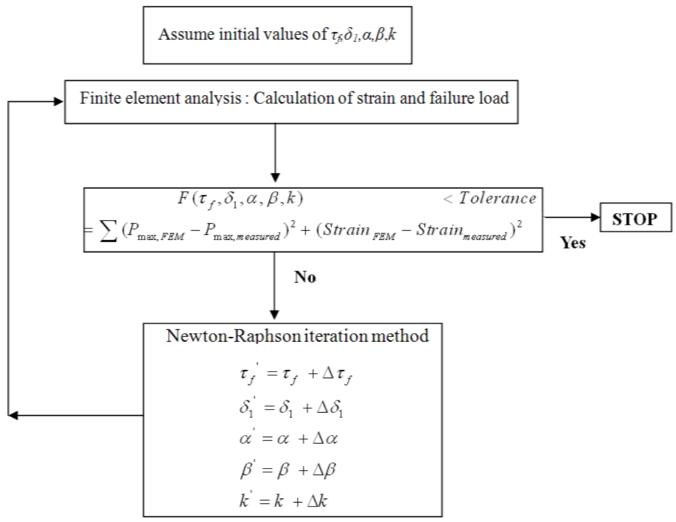


Fig. 11. Flow chart of numerical procedure

behaviors. From the strain distributions including Fig. 4 an d failure load depicted in Figs. 5-7, 5-parameters τ_f, δ_1, k, α and β can be obtained from the inverse analysis, which is implemented with Newton-Raphson iteration method. The o verall procedure is shown in Fig. 11.

B. Effects of bond length, width and concrete compressive strength on bond parameters

The parameters τ_f, δ_1, k, α and β for proposed bond-slip model obtained from the inverse analysis are depicted in Figs. 12-18. As shown in Figs. 12-17, the parameters τ_f, δ_1, and k, which represent bond strength, bond slip at bond strength, and interfacial fracture energy, respectively, are influenced by concrete compressive strength and bonded width. Three parameters increase as concrete compressive strength increases, and decrease as bonded width increases. Especially for the bonded width effect, the parameters τ_f, δ_1, k are linearly decreasing with increasing bonded width. As for the bonded length, it is concluded that there is no significant effect on three parameters from the fact that linear fitting algorithm produced very small gradient ranged below 10^{-3}. As for the two parameters α and β, which determine the separating point in linear elastic ascending part of bond-slip model, α and β have constant values 0.544 and 0.639, respectively, neglecting small gradient with respect to bond length, as shown in Fig. 18. According to the studies by Nakaba et al. [11], Savioa et al. [16], and Ueda et al. [6], α and β were considered as 0.5 and 0.7, respectively. Accordingly, it is concluded that the results of this study are closer to a linear relationship in ascending branch than other results.

On the other hand, strain distributions from the finite

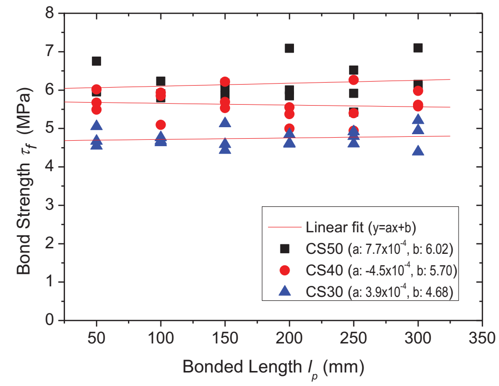


Fig. 12. Effect of bonded length on τ_f

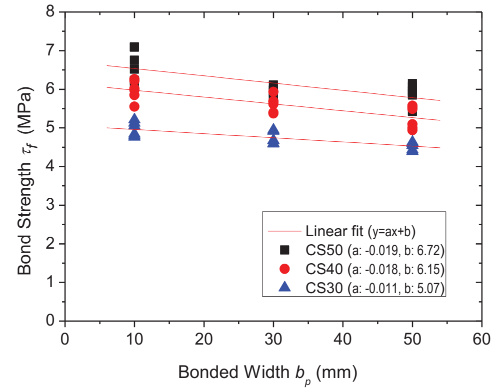


Fig. 13. Effect of bonded width on τ_f

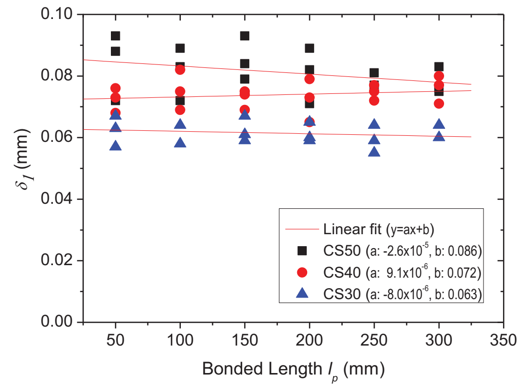


Fig. 14. Effect of bonded length on δ_1

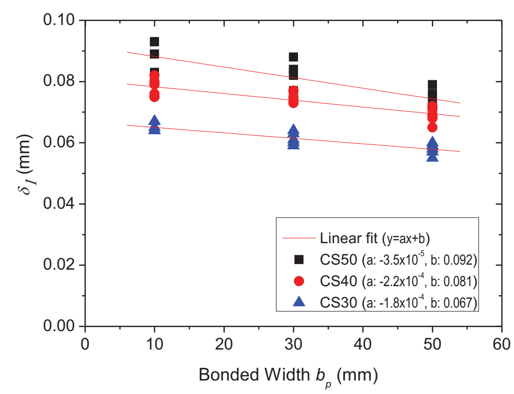


Fig. 15. Effect of bonded width on δ_1

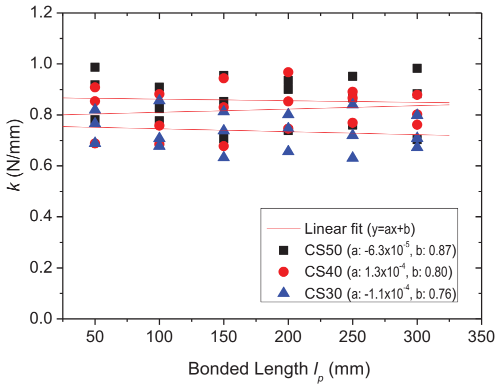


Fig. 16. Effect of bonded length on parameter k

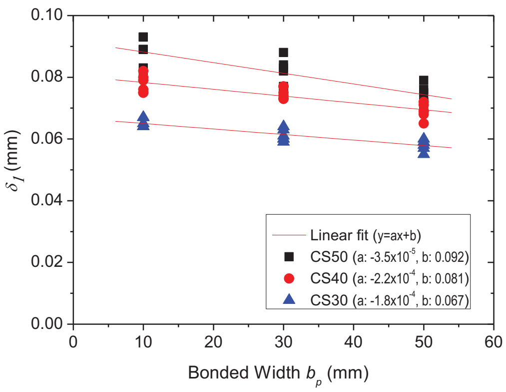


Fig. 17. Effect of bonded width on parameter k

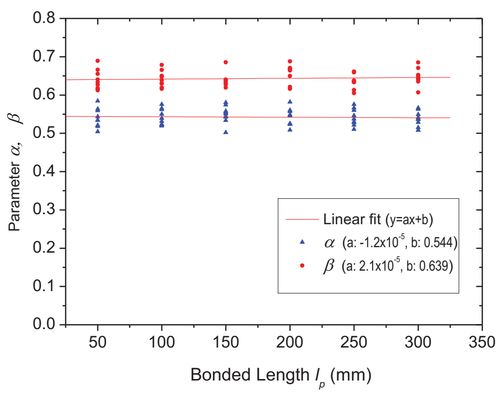
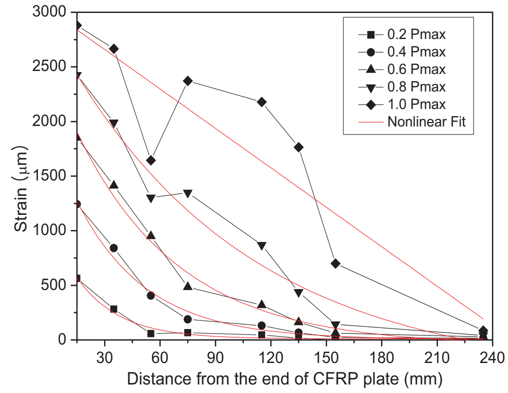


Fig. 18. Effect of bonded length on parameter α and β



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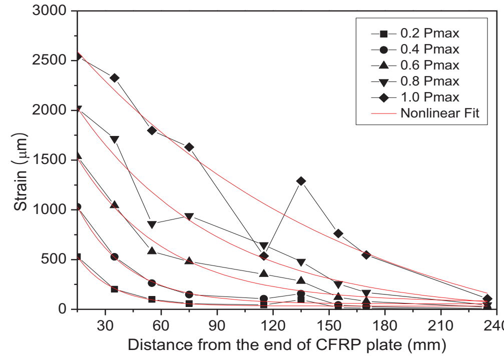

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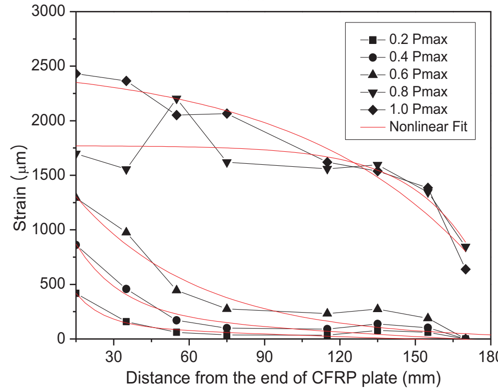

(c)

Fig. 19. Comparisons of numerical and experimental results on strain distribution of CFRP plate (bond width = 50 mm). (a) Bond length 250 mm (CS30). (b) Bond length 250 mm (CS40). (c) Bond length 250 mm (CS50)

element analyses using 5-parameters are comparable with ones from the pull-tests in Fig. 19. Excluding some scatters and differences at failure load, it can be concluded that the FEA results implemented with 5 parameters effectively represent the pull-test results.

IV. CONCLUSIONS

This study investigated the effects of bond length, bond width and concrete strength on the interfacial behavior of CFRP-bonded concrete and a bond-slip model is suggested based on the experimental results.

1) From the pull test for CFRP-bonded concrete, it is observed that the bond strength represented by failure load increases as the bond width increases from 10 mm to 50 mm and the effect of concrete strength is minor.

2) A bond-slip model, which is represented by bi-linear ascending branch followed by exponentially descending branch, is suggested. Based on experimental results, the inverse analysis method for determination of a bond-slip model is carried out.

3) From the inverse analysis, five parameters constituting the bond-slip model are obtained and each parameter is analyzed by the regression fit with linear function of bond length and bond width. From the parametric study, it is found that five parameters of the suggested bond-slip model can be considered constant with respect to bond length in contrast with bond width, which has a linearly decreasing relationship with each

parameter.

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REFERENCES

[1] Teng J.G., Chen J.F., Simth S.T., Lam L., "FRP-strengthened RC structures", John Wiley & Sons, 2002

[2] Chen J.F., Teng J.G., "Anchorage strength models for FRP and steel plates bonded to concrete", *Journal of Structural Engineering, ASCE*, Vol.12, No.7, pp784-91, 2001.

[3] Yao J., Teng J.G., Chen J.F., "Experimental study on FRP-to-concrete bonded joints", *Composites-Part B: Engineering*, Vol.36, No.2, pp99-113, 2005.

[4] Brosens K., van Gemert D., "Anchoring stresses between concrete and carbon fiber reinforced laminates", *Proceedings of 3rd international symposium on non-metallic (FRP) reinforcement for concrete structures*, pp271-278, JCI, 1997.

[5] Dai J.G., Ueda T., "Local bond stress slip relations for FRP sheets-concrete interfaces", *Proceedings of 6th international symposium on FRP reinforcement for concrete structures*, pp143-152, World Scientific Publications, 2003.

[6] Ueda T., Dai J.G., Sato Y., "A nonlinear bond stress-slip relationship for FRP sheet-concrete interface", *Proceedings of international symposium on latest achievement of technology and research on retrofitting concrete structures*, pp113-120, 2003.

[7] Yuan H., Teng J.G., Seracino R., Wu Z.S., Yao J., "Full-range behavior of FRP-to-concrete bonded joints", *Engineering Structures*, Vol.26, No.5, pp553-564, 2004.

[8] Sato Y., Kimura K., Kobatake Y., "Bond Behaviors between CFRP Sheet and Concrete", *Journal of Structural and Construction Engineering*, Vol.500, pp75-82, 1997 (in Japanese).

[9] Lorenzis L.D., Miller B., Nanni A., "Bond of Fiber-Reinforced Polymer Laminates to Concrete", *ACI Material Journal*, Vol.98, No.3, pp256-264, 2001.

[10] Yoshizawa H., Wu Z., Yuan H., Kanakubo T., "Study on FRP-Concrete Interface Bond Performance", *Transactions Japan Society of Civil Engineers*, Vol.662, No.49, pp105-119, 2000.

[11] Nakaba K., Toshiyuki K., Tomoki F., Hiroyuki Y., "Bond Behavior between Fiber-Reinforced Polymer Laminates and Concrete", *ACI Structural Journal*, Vol.98, pp359-367, 2001.

[12] Sato Y., Asano Y., Ueda T., "Fundamental Study on Bond Mechanism of Carbon Fiber Sheet", *Concrete Library International JSCE*, Vol.37, pp97-115, 2000.

[13] Leung C.K.Y., Tung W.K., "Three-Parameter Model for Debonding of FRP Plate from Concrete Substrate", *Journal of Engineering Mechanics*, Vol.132, No.5, pp509-518, 2006.

[14] Pan J., Leung C.K.Y., "Effect of Concrete Composition on FRP/Concrete Bond Capacity", *Journal of Composites for Construction*, Vol.11, No.6, pp611-618, 2007.

[15] Yuan H., Wu Z., Yoshizawa H., "Theoretical Solutions on Interfacial Stress Transfer of Externally Bonded Steel/Composite Plates", *Journal of Structural Mechanics and Earthquake Engineering JSCE*, Vol.18, No.1, pp27-39, 2001.

[16] Savioa M., Farracuti B., Mazzotti D., "Non-Linear Bond-Slip Law for FRP-Concrete Interface", *Proceedings of 6th International Symposium on FRP Reinforcement for Concrete Structures*, pp163-172, World Scientific Publications, 2003.