- Technical Paper -

A STUDY ON BOND MECHANIS OF FIBER REINFPORCED POLYMER BONDED TO CONCRETE

Dae-Eon Kang*1, Hyun-Su Woo*2, Waon-Ho Yi*3, Young-Chan, Yoo*4

ABSTRACT
This paper intends to extract the main parameters enabling the evaluation of the bond mechanism between FRP and concrete through comparative study of the formulae proposed by previous researchers. Previous experimental results were gathered as reference to examine the effects of these parameters and, to derive and propose formulae. Double shear tests were also performed to investigate the bonding characteristics between concrete and FRP and, verify the validity of the proposed formulae through comparison with previous formulae.
Keywords: fiber reinforcement polymer, bond strength, effective bonded length, stiffness, concrete strength, de-lamination of FRP

1. INTRODUCTION

FRP reinforcing methods, apart from the attractive features provided by the high strength, lightweight, resistance to corrosion and constructability of FRP materials, are increasingly utilized instead of previous reinforcement techniques owing to the high-tech image given by the application of innovative materials as construction material and are promising for wider exploitation in the future.

However, the material properties of FRP reinforcement methods using innovative materials being still insufficiently investigated, direct application of the current criteria becomes delicate. Expecting to achieve desired reinforcing effect appears thus as a difficult task and may result in serious safety problems.

Due to these factors, the international community undertook various researches to examine the basic properties of FRP and numerous experimental studies relative to the reinforcing effects of reinforced concrete members strengthened with FRP. However, the absence of systematic evaluation methods or experimental criteria related to bond performance affects the objectivity of these research results. Especially, researchers reported recently the close relationship of the bond mechanism in shear reinforcement method using externally bonded FRP. Since quantitative evaluation of the bond performance between FRP and concrete has not been established to date, these researchers developed individual evaluation methods for the effective bond length, which makes it difficult to pretend that objective evaluation has been realized.

Following, in order to investigate the bond mechanism between FRP and concrete, this study selected major parameters through comparative analysis of formulae proposed by previous researchers. Previous experimental results were gathered as reference to examine the effects of these parameters and propose formulae. Double shear tests were also performed to derive a method assessing objectively the effective bond length and the validity of the proposed formulae was verified through comparison with previous formulae.

2. TEST PROGRAMS SURVEY OF ISSUES IN PREVIOUS STUDIES

2.1 Maeda et al. (1997)[1]

Maeda et al. performed double shear tests to investigate the bonding characteristics between concrete and carbon fiber sheets, and proposed a predictive formula for the bond strength.

*1 Research Associate Professor, Dept. of Structural Engineering, Kwang-Woon University, Korea
*2 Graduate Student, Dept. of Structural Engineering, Kwang-Woon University, Korea
*3 Professor, Dept. of Structural Engineering, Kwang-Woon University, Korea
*4 Chief researcher, Dept. of Structural Reaserch, Korea Institute of Construction Technology, 2311 Daewha-Dong Ilsan-Gu, Goyang-Si Gyeonggi-Do, Korea

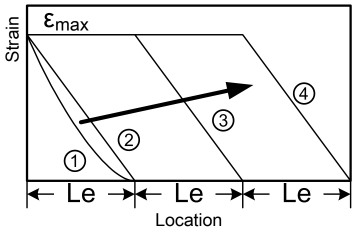


Fig. 1 Schematic strain distribution

The schematization of the strain distribution illustrated in Fig. 1 was used to calculate the effective bond length (Le). Maeda reported that the strain distribution draws a second order curve (①) during the initial loading stage to become linear (②, ③, ④) at the maximum loading stage. Even if the stiffness of the FRP reinforcement (Eftf) was considered as experimental variable, the investigation remained limited to 1 and 2 carbon fiber sheets without consideration of newly developed FRP products using hyper-elastic materials. As a result, Maeda assumed a definite slope of the strain distribution regardless of the stiffness of the reinforcement, and asserted that the effective bond length was inversely proportional to the stiffness of the reinforcement.

Maeda formulated Equation (2) for the evaluation of the effective bond length from the strain distribution and suggested Equation (1) to predict the bond strength. As expressed in Equation (2), the evaluation assumes that the effective bond length is inversely proportional to the stiffness of the reinforcement.

$$P_{\max} = L_e \cdot b_f \cdot \tau_{bu} \qquad (1)$$

$$L_e = \exp\left[6.314 - 0.580 \ln\left(t_f \times E_f\right)\right] \qquad (2)$$

$$\tau_{bu} = E_f t_f \left(\frac{d\varepsilon}{dx}\right)_0 \qquad (3)$$

Where,

L_e is the effective bond length (mm), b_f is the width of the FRP reinforcement (mm), t_f is the thickness of the reinforcement (mm), E_f is the modulus of elasticity of the reinforcement (MPa), $(d\varepsilon / dx)_0$ is the slope of the strain distribution (=$110.2\mu m$).

On the other hand, recently published papers[2] reported that the effective bond length increases proportionally to the stiffness of the reinforcement, which open further discussion concerning the formula proposed by Maeda.

2.2 Horiguchi and Saeki (1997)[3]

Horiguchi and Saeki (1997) performed bond tests on concrete and FRP considering the compressive strength of concrete as experimental variable and estimated the influence of this parameter on the bonding performance of concrete. Three types of tests, conducted for compressive strengths of concrete of 10.5MPa, 31.4MPa, 46.1MPa, revealed that the final failure of all the specimens occurred due to the delamination of FRP. From the analysis of experimental results, Horiguchi derived the following Equation (4) relative to the bond performance of concrete and FRP.

$$f_{bok} = 0.09 f_{ck}^{(2/3)} \qquad (4)$$

Where,

f_{bok} stands for the bond stress.

2.3 Khalifa et al. (1998)

Khalifa et al. (1998) conducted researches to evaluate the shear strength of RC beams shear-reinforced with FRP. Differently from previous studies, 2 different formulae were proposed according to 2 different types of failure mode. The first mode corresponded to failure due to the rupture of FRP, while the second failure mode occurred due to delamination. For the first mode, Khalifa assumed that shear strengthening performance can be evaluated by applying a certain strength reduction coefficient on the maximum tensile stress of FRP (Equation 1). For the second mode, Khalifa stated that, since the effect of shear strengthening is determined by the bond mechanism of concrete and FRP before FRP reaches its maximum tensile stress, shear strengthening performance can be evaluated regard to the bond performance of concrete and FRP (Equation 2). Moreover, in the case of RC beams shear-strengthened with externally bonded FRP, Khalifa stressed the consideration of bond mechanism in Equation (2) since FRP delamination-failure mode is dominant.

After the achievements of Khalifa, researchers accounted for the bond mechanism in shear strengthening. The design criteria for shear strengthening using externally bonded FRP prescribed in ACI 440.2R-02 were also drawn up based on his research results. Moreover, the criteria related to the participation ratio of FRP in the shear strengthening is recently used in Korea.

It should be noted that previous criteria equations or shear strengthening formulae derived with respect to the research results of Khalifa are accounting for the bond performance. However, they are applying the equation for the bond performance suggested by Maeda et al. (1997) without any verification, which also opens large issues for further investigations.

2.4 Chen and Teng (2001) [4]

Based on the formula proposed by Holzenkämpfer (1994) for the prediction of bond performance in externally bonded steel plate reinforcement method, Chen and Teng derived an equation concerning the bond performance of concrete and FRP. In order to evaluate the effectiveness of the predictive formula, Chen and Teng analyzed previous experimental results obtained from single and double shear test, and conducted comparative study of the formulae proposed by each researcher. The study revealed that the effective bond length is increasing proportionally to the stiffness of the FRP reinforcement, and led to conclusions disagreeing with the results of Maeda who stated that the strain distribution exhibited definite slope regardless of the stiffness of the reinforcement. Equation (5) expresses the predictive formula suggested by Chen and Teng for the bond performance.

$$P_U = 0.427\beta_P\beta_L\sqrt{f_c'}\,b_f L_e \qquad (5)$$

$$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_c'}}} \qquad (6)$$

$$\beta_P = \sqrt{\frac{2 - b_f/b_c}{1 + b_f/b_c}} \qquad (7)$$

$$\beta_L = \begin{cases} 1 & \text{if } L \geq L_e \\ \sin\dfrac{\pi L}{2L_e} & \text{if } L \prec L_e \end{cases} \qquad (8)$$

Where, b_c is the width of the concrete section, β_P is a constant related to the width ratio of reinforcement and concrete, β_L is a constant relative to the effective bond length and bond length.

Following, further examination should also be carried out since this approach disagrees with the bond characteristics of concrete and FRP presented by Khalifa, who stated that bond mechanism due to delaminating occurring at the concrete interface is governing.

3. PROPOSED FORMULA FOR THE EVALUATION OF BONDING PERFORMANCE

As mentioned above, the main parameters influencing the bond strength are the effective bond length, the strength of concrete and the stiffness of reinforcement. It has also been seen that the main variables for the effective bond length are constituted by the strength of concrete and the stiffness of reinforcement. Table 1 summarizes the database gathering and arranging previous experimental data[4],[5] which were used to derive a formula for the effective bond length through regression analysis.

Table 1 Experimental data collected from references

	Concrete Strength (MPa)	Stiffness of FRP (GPa x mm)	Maximum experimental load (kN)	Effective bond length (mm)
C5-ARF	57.6	24.04	11.79	65.9
C5-HCF	57.6	70.14	21.60	120.3
C5-SCF	57.6	43.60	16.35	95.7
C5-SCFH	57.6	87.19	25.63	133.5
C5-SCFL	57.6	21.80	11.48	63.5
M5-ARF	49	24.04	12.43	70.3
M5-HCF	49	70.14	16.37	121.2
M5-SCF	49	43.60	15.70	96.6
M5-SCFH	49	87.19	22.29	134.1
M5-SCFL	49	21.80	9.35	67.0
M2	40.8	25.3	9.2	-
M3	40.8	25.3	11.95	-
M7	42.7	50.6	16.25	-
M8	44.7	25.3	10	-

3.1 Formula proposed for the evaluation of the effective bond length (**L_e**)

This study suggests a formula for the estimation of the effective bond length based on the equation proposed by Chen and Teng (Equation 5). Assuming that the effective bond length is 0 (zero) if any of the strength of concrete or the stiffness of reinforcement becomes 0 (zero), the basic formulation of the proposed formula is defined by Equation (9) expressed in terms of powers of each variable.

$$L_e = \alpha\, f_{ck}^{\beta}\,(E_f t_f)^{\gamma} \qquad (9)$$

Fig. 2 illustrate the effects of the strength of concrete and stiffness of reinforcement on the effective bond length.

As shown in Fig. 2, the effective bond length approaches $f_{ck}^{-0.2}$ and tends to approximate $(E_f t_f)^{0.5}$. Results of the regression analysis performed on the collected data reveal that α = 1.002148 with a correlation factor R of 99.9%. A simplification of the formula can be expressed by Equation (10).

$$L_e = f_{ck}^{-0.2} (E_f t_f)^{0.5} \quad (10)$$

3.2 Formula proposed for the evaluation of bond strength(P_u)

The main variables expected to influence the bond strength are the effective bond length, the strength of concrete and the stiffness of reinforcement, as has been foreseen above. Since the effective bond length is expressed in terms of the strength of concrete and the stiffness of reinforcement, the formula proposed for the evaluation of the bond strength can be expressed in terms of these variables. Assuming that the bond strength is 0 (zero) if any of these parameters becomes 0 (zero), the proposed formula may be formulated by Equation (11).

$$P_u = \beta\, f_{ck}^{\gamma} (E_t f_t)^{\delta} b_f \quad (11)$$

Fig. 3 illustrate the effects of the strength of concrete and stiffness of reinforcement on the bond strength.

Analysis related to the influence of the main parameters on the bond strength shows that the bond strength tends to approximate $f_{ck}^{0.8}$ and $(E_f t_f)^{0.5}$. Results of the regression analysis performed on the collected data reveal that β= 0.063597 with a correlation factor R of 99.9%. A simplification of the formula can be expressed by Equation (12).

$$P_u = 0.06\, f_{ck}^{0.8} (E_t f_t)^{0.5} b_f \quad (12)$$

Introducing Equation (12) into Equation (9) proposed for the evaluation of the effective bond length leads to Equation (13).

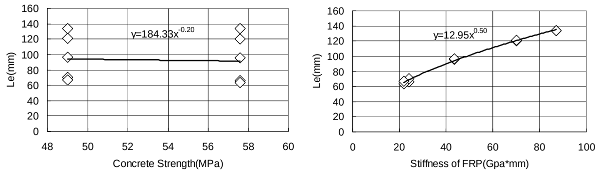
$$P_u = 0.06\, f_{ck} L_e b_f \quad (13)$$

Where P_u is expressed in N.

3.3 Examination of the formula proposed for the evaluation of bond performance

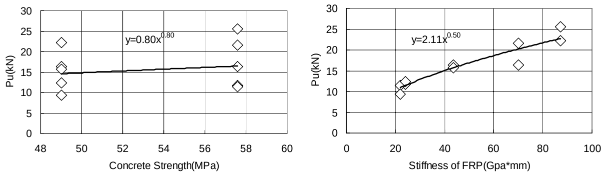
Fig. 4 compare the experimental results of the effective length and bond strength using the data arranged in Table 2 and the values calculated by means of the proposed formulae. Mreover, the values computed according to the equations proposed by Maeda and Chen and Teng are also plotted in each of the figures for comparison.

4. EXPERIMENT



(A) concrete strength (B) stiffness of FRP

Fig. 2 Effects of the strength of concrete and stiffness of FRP on L_e



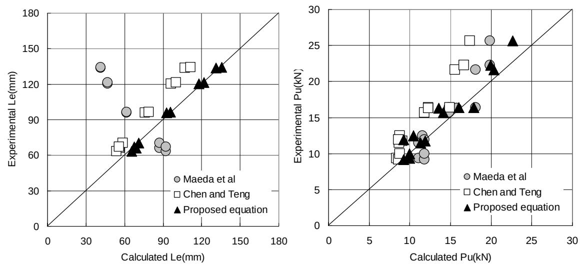
(A) Concrete Strength (B) Stiffness of FRP

Fig. 3 Effects of the strength of concrete and stiffness of reinforcement on Pu

In order to examine the effectiveness of the formulae proposed to assess the effective bonding length and bond strength presented in Chapter 3, double tensile shear tests were carried out on concrete reinforced with FRP. The experimental variable adopted for the tests was the strength of the reinforcing material expected to have the largest effect on bond performance.

4.1 Preparation of specimens

Fig. 5 illustrates the shape of the specimens.



(A) Effective bond length (B) ultimate bond strength

Fig. 4 Comparison with calculated values and experimental values

Taking reference to JSCE-E 543-2000[6], two concrete blocks (100×100×400) reinforced with steel bar D19 protruding by 150mm at both extremities were manufactured. Ready-mix concrete with design compressive strength of 30MPa was used for the blocks. The FRP reinforcements used for the tests were 1-directional carbon fiber sheet and carbon fiber plate and, bi-directional fiber reinforcement constituted by glass fiber sheet. In addition, impregnation epoxy and bonding epoxy were mixed as two-component type resin with matrix to hardening agent ratio assigned for each product and cured at 20ºC during 7 days before testing. Tables 2 to 4 summarize the test results for each material.

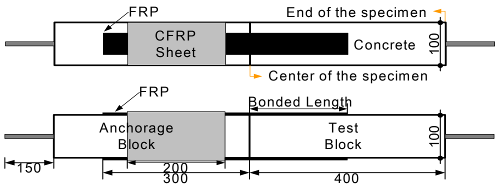


Fig. 5 Shape of specimen

Table 2 Test results for concrete

Design Compressive strength (MPa) 28days	Test result (MPa)	Young's modulus (MPa)
30	26.26	2.45×104

Table 3 Test results for FRP

Type of FRP	Thickness of FRP (mm)	Tensile strength (MPa)	Young's modulus (MPa)	Ultimate Elongation (%)
		Test result	Test result	Test result
Carbon fiber sheet	0.11	4,130	2.63×105	1.65
Glass fiber sheet	1	746	3.20×104	2.52
Carbon fiber plate	1.3	2,795	1.71×105	1.74

Table 4 Test results for epoxy

Type of epoxy		Compressive strength (MPa)	Tensile strength (MPa)	Bending strength (MPa)	Shear strength (MPa)
Carbon fiber sheet	Test result	63.41	31.36	48.02	10.78
Glass fiber sheet	Test result	103.1	57.23	152.39	12.25
Carbon fiber plate	Test result	-	23.62	-	5.19

4.2 Loading and measurement methods

The loading proceeded using a 25tonf actuator fixed on a prefabricated frame. The applied loading speed complied with JSCE-E 543-2000[] at 0.5mm/min (2~5kN/min). The tensile strain of the FRP reinforcement was measured during loading by means of strain gauges disposed at intervals of 20mm along the length of the bonded length.

4.3 Experimental results

(1) Bond load

Table 5 summarizes the test results. The failure of most of the specimens occurred through the delamination of FRP reinforcement with concrete. In the case of CS5 and GS3, the bond strength being larger than the tensile strength of concrete, splitting tensile failure occurred in concrete. It can be seen in Table 3 that the bond load increases as the stiffness of the reinforcement.

(2) Stiffness and strain distribution of reinforcement

Table 5 Test results

Type of FRP	Name of specimens	Number of FRP (Ply)	Bond length (mm)	Cracking load (kN)	Maximum load (kN)
Carbon fiber Plate	CP1	1	200	24.5	24.5
Carbon fiber sheet	CS1	1	200	12.15	15.68
	CS2	2	200	16.56	25.38
	CS3	3	200	24.79	30.58
	CS4	4	200	33.71	36.75
	CS5	5	200	-	-
Glass fiber sheet	GS1	1	200	24.5	24.5
	GS2	2	200	24.5	24.5
	GS3	3	200	-	-

Fig. 6 depicts the strain distribution in the FRP reinforcement according to the loading stages. The stress concentrates at center of the specimen during initial crack loading stage to progress gradually toward the extremities of the FRP reinforcement as the load increases. In addition, the slope of the strain distribution varies as the number of FRP reinforcements increases regardless of the type of reinforcement. This observation is in contradiction with Maeda[1] who stated that the slope of the stain distribution was definite regardless of the stiffness of the reinforcement.

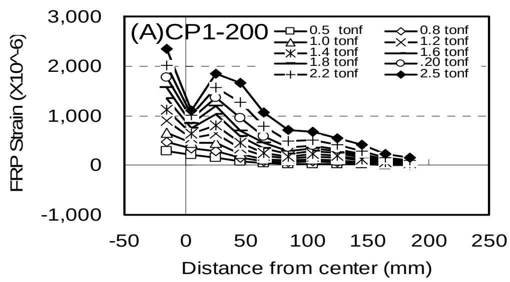


Fig. 6 Strain distribution in the FRP according to the loading stages

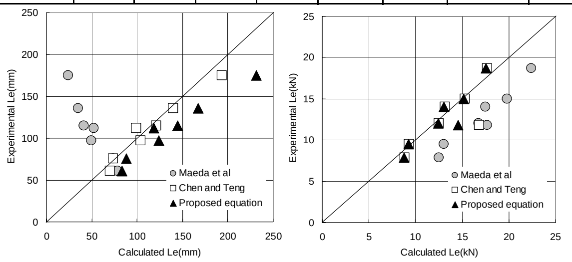
4. EXPERIMENTAL VERIFICATION OF THE PROPOSED FORMULA

Table 6 presents the values of the effective bond length and bond strength calculated by means of the formulae proposed in this study (Equations 10 and 13) and the equations suggested by Maeda (Equations 1 and 2) and by Chen and Teng (Equations 5 and 6), as well as the experimental values. Fig. 7 compare the computed and experimental values of the effective bond length and bond strength, respectively.

It can be seen that, for the effective bond length, the values obtained using the formula proposed by Maeda are in conflict with the experimental results, while giving good approximations of the bond strength, but

Table 6 Comparison with the computed values and experimental values

Type of specimens	Results of experiment		Maeda		Chen and Teng		Proposed equation	
	Le (mm)	Pu (kN)	Le (mm)	Pu (kN)	Le (mm)	Pu (kN)	Le (mm)	Pu (kN)
CP1	175	11.76	20.10	24.57	202.2	26.78	239.4	12.68
CS1	61	7.84	70.74	9.88	68.36	7.92	80.96	7.15
CS2	112	12.01	47.32	13.22	96.68	11.20	114.4	10.11
CS3	115	14.99	37.40	15.67	118.4	13.71	140.2	12.38
CS4	136	18.72	31.66	17.69	136.7	15.83	161.9	14.29
GS1	76	9.48	71.79	9.78	67.50	7.82	79.93	7.05
GS2	97	14.04	48.03	13.08	95.46	11.05	113.0	9.98



(A) Effective bond length (B) ultimate bond strength

Fig. 7 Comparison with calculated values and experimental values

Table 7. Compare the Proposed equation and previous researcher's equation

Type of equation	Bond strength		
	Correlation factor	The average ratio	Standard deviation
Proposed equation	99.5%	0.98	0.090
Maeda	99.6%	0.73	0.068
Chen and Teng	99.0%	0.95	0.120

overestimate them for all specimens presenting large stiffness of the FRP reinforcement (CP1). Chen and Teng predict accurately the experimental values of the effective bond length but produce overestimated results for specimens presenting large stiffness of the reinforcement, similarly to Maeda.

On the other hand, the formula proposed in this study is seen to overestimate slightly the experimental values of the effective bond length and underestimate slightly the bond strength. Especially, it can be observed that relatively accurate values are predicted even for specimens presenting large stiffness of the reinforcement.

Table 7 lists the correlation factor (R) of the experimental values, the average ratio of the experimental values to the computed values ($\overline{X}$) and the standard deviation (σ) in order of evaluate the exactness of the proposed formulae.

5. Conclusions

This study made it possible to draw the following conclusions.

(1) The variables determining the effective bond length are the strength of concrete and the stiffness of the FRP reinforcement. It was seen that the effective bond length tends to be inversely proportional to the strength of concrete and proportional to the stiffness of the FRP reinforcement.

(2) The variables determining the bond strength are the effective bond length, the strength of concrete and the stiffness of the FRP reinforcement. It was seen that the bond strength tends to increase proportionally to each of these variables.

(3) This study proposed the following predictive formulae for the effective bond length and bond strength based on a database gathering the experimental values produced by previous researchers.

$$L_e = f_{ck}^{-0.2}(E_f t_f)^{0.5}, \quad P_u = 0.06 f_{ck} L_e b_f$$

References

[1] Toshiya Maeda at all(1997), "A Study on Bond Mechanism of Carbon Fiber Sheet.", Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third International Symposium, Sapporo, Japan, pp. 279～285

[2] CSA S806-02, Annex P(Informative), "Test Methods for Bond Strength of FRP Sheet Bonded to Concrete", Canadian Standards Association, May 2002, pp 140～149

[3] Takashi Horiguchi and Noboru Saeki(1997), "Effect of Test Methods and Quality of Concrete on Bond Strength Of CFRP Sheet", Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third International Symposium, Sapporo, Japan, pp. 265～270

[4] Chen and Teng(2001), "Anchorage Strength Models for FRP and Steel Plates Bonded to Concrete", Journal of Structural Engineering, July 2001, pp. 784～791

[5] Kasumassa Nakaba et al(2001), "Bond Behavior between Fiber-Reinforced Polymer Laminates and Concrete", ACI Structural Journal, May 2001, ACI, pp 359～367

[6] JSCE-E 543-2000, "Test method for bond properties of continuous fiber sheets to concrete"