KCI CONRETE JOURNAL
Vol.14 No.1, March 2002, pp.1-7

Flexural Strength Evaluation of RC Members Laminated by Carbon Fiber Sheet

Hae-Geun Park[1)*]

[1)] *Ph.D, Civil Engineering Technology Team, SAMSUNG Corporation, Engineering & Construction Group, Korea*

(Received June 5, 2001; Accepted December 24, 2001)

Abstract

This paper reports the experimental and analytical investigations for evaluating the flexural strength of a RC slab strengthened with carbon fiber sheet (CFS). The evaluation of the ultimate flexural strength of a slab is tried under the assumption that the failure occurs when the shear stress mobilized at the interface between the concrete bottom and the glued CFS reaches its bond strength. The shear stress is evaluated theoretically and the bond strength is obtained by a laboratory test. The ultimate flexural strength is obtained by flexural static test of the slab specimen, which corresponds to the part of a real slab. From the results, the new approach based on the bond strength between concrete and CFS looks feasible to evaluate the flexural strength of the CFS and RC composite slab.

***Keywords** : flexural strength, interfacial bond behavior, carbon fiber sheet*

1. Introduction

In recent years, Fiber Reinforced Plastic (FRP) materials have been used to rehabilitate many types of structures including bridges, parking decks, smoke stacks, and buildings with its superior characteristics such as high strength and stiffness per unit weight, easier handling due to their lightweight, and corrosion resistance. Numerous technical papers[1-3)] have revealed that FRP composite systems bonded to various structural members can significantly increase their stiffness and load carrying capacity beyond what can be achieved through conventional methods.

However, many experimental results show that flexural failures of RC members glued by FRP at the bottom are apt to occur by sudden delamination of FRP from the concrete surface. This phenomenon indicates that the bond strength between concrete and FRP is considered as one of the important factors to determine the actual strength of RC members retrofitted with FRP materials. Because of this reason, extensive analytical researches[4-5)] of the RC members and studies[6-9)] of interfacial bond behavior between concrete and FRP materials have been performed, and also further investigation is necessary to provide a better understanding of failure mechanisms of FRP and RC composite members.

This paper reports the experimental and analytical investigations for evaluating the flexural strength of RC slabs strengthened with Carbon Fiber Sheet (CFS).

2. Experiment

2.1 Flexural static test

Flexural static test was performed with slab specimens. Each test slab was almost identical to the real slab of a highway viaduct in terms of the amount of reinforcement, quality of concrete and the thickness of the slab. This test slab represented a part of the real slab with the same flexural moment capacity. Each test slab had a rectangular cross-section of 370mm width, 180mm depth, and overall length of 2000mm.

To ensure a good bond between concrete and CFS, the surface of the test slabs were cleaned and sanded to obtain a rough surface, and then primer was applied in the bonding surface of the slab with roller brush. After the primer cured, a coat of epoxy resin was applied onto the concrete surface.

The CFS, previously cut to the required dimensions, was

* *Corresponding author*
Tel.: +82-2-2145-6040; Fax.: +82-2-2145-6050
E-mail address: hgpark68@samsung.com

positioned on the prepared concrete surface, and an epoxy resin was applied. A similar procedure was repeated while applying additional layers. The CFS was glued at the bottom of the test slab. After the CFS was bonded, 7-day resin curing was performed at the ambient conditions.

Fig. 1 shows the loading set up. Flexural static test with 6.1 shear-span ratio (a/d) was conducted under four-point flexural load. All test slabs were simply supported and subjected to two concentrated loads symmetrically placed about the mid-span. Table 1 shows properties of the materials used in this experiment. Normal type of CFS with 300g/m^2 in weight (T300) or 400g/m^2 (T400) were used for the strengthening. Unidirectional CFS was applied to the total length of slab specimen.

2.2 Bond test

Interfacial bond behavior between concrete surface and CFS (actually epoxy layer) was investigated by laboratory test. Each rectangular concrete prism specimen had 100mm width x 100mm depth x 200mm length. The two bonding faces of each prism specimen were prepared by grinding and cleaned, and then primer was applied to the concrete surface. Unidirectional CFS (100mm length x 37mm width) was glued with epoxy resin to bonding surfaces as shown in Fig. 2. The material properties of used in bond test were almost same as the static test. Two different types of CFS were considered as main variables. Fig. 3 shows the loading set up in bond test. All specimens were statically loaded and strains of CFS were recorded. The strains were measured by strain gages mounted on CFS at spacing of every 20mm. Only two specimens were tested for each case.

3. Results of the test & discussion

3.1 Flexural static test results

Table 2 shows the flexural static test results. Fig. 4 shows the typical failure pattern. From the static test, the following information was obtained.

(1) All test slabs retrofitted with CFS showed significant increases in ultimate flexural strength as compared to the control slab. Retrofit of the test slab with 2 layers of T400 CFS improved the flexural strength over 2 times.

(2) Failure of the test slab occurred immediately after delamination of CFS from concrete and crushing of concrete in the compression zone followed at the same time. At this time, the strain level developed in CFS was much lower than its rupture strain. Therefore,

Table 1 Properties of material used

Material	Properties			
Concrete steel epoxy	Compressive strength : 39.2 N/mm^2 Yield strength : 341 N/mm^2 (D16) Tensile strength : 55.3 N/mm^2			
CFS	Weight (g/m^2)	Thickness (mm)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)
T 300 T 400	300 400	0.167 0.222	3430	2.53×10^5

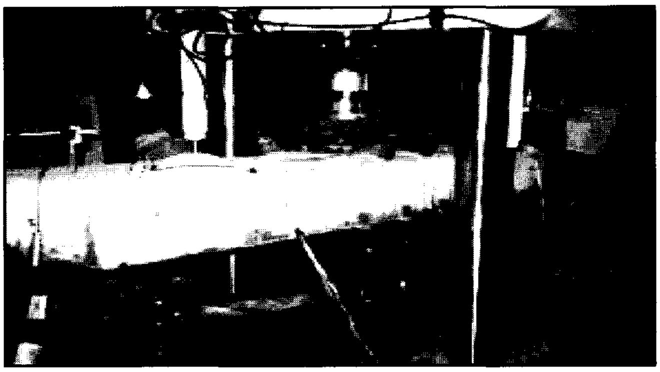


Fig.1 Flexural static test

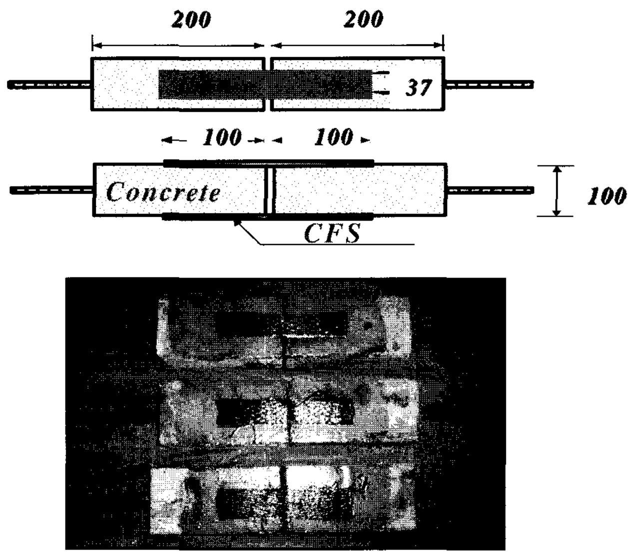


Fig. 2 Bond test specimen (mm)

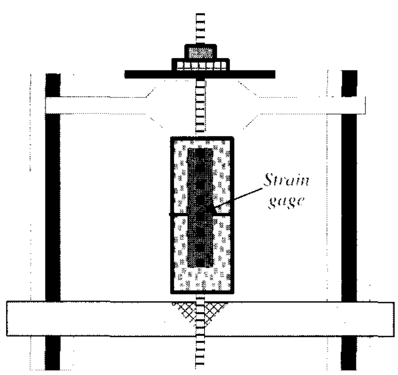


Fig. 3 Bond test loading set-up

improvement of bond strength between concrete and CFS is expected further improvement of the flexural strength of the slab.

3.2 Bond test results

Table 3 is the summary of the bond test results. The failure of test specimens mainly occurred by sudden delamination of CFS from the concrete surface before reaching its rupture strain. It is also found that the maximum pull load increases as the thickness of bonded CFS increases. Fig. 6 shows measured strain distributions developed in the CFS just before the slipping. It can be seen that strain distributions between concrete and CFS is not uniform along the bonded length.

3.2.1 Evaluation of bond strength

Executing tensile test of the bond specimen as shown in Fig. 2, the bond strength f_B is evaluated by the following two methods.

*Method 1

The average bond strength is defined as;

$$f_B = P_{max} / 2A \qquad (1)$$

Where, P_{max} : Maximum pull load, A : Attached area of *CFS* ($= b\ L$), b : Bonded width (=37mm), L : Bonded length (=100mm)

In this method, if the bonded length increases, the ultimate load increases. However, the average bond strength decreases as the bonded length increases, because the ultimate load is not increased in proportion to the bonded length.

Table 2 Static test results

Test slab	CFS	P_{max} (kN)	Strength improvement	Strain of CFS at failure (μ)
Control	No CFS	91.7	1.0	
S-1	T300 2layers	157.8	1.72	6000 (40.1)
S-2		165.6	1.81	7310 (49.1)
S-3	T400 2layers	198.0	2.16	Not available

* ( ):The ratio of CFS strain at failure to its rupture strain in %.
* The value of control slab is the average of 2 test slabs.

Table 3 Bond test results

Test specimen	CFS	Bond length(mm)	Section area(mm^2)	*Ultimate load(kN)*
B-1	T300 2layers	100	12.36	9.1
B-2				12.5
B-3	T400 2layers		16.48	14.0
B-4				16.0

*Method 2

Fig. 7 shows measured strain distributions between concrete surface and CFS just before the slipping. From the measured strains of the CFS at the surface, bond stresses can be evaluated as follows. Also, the bond strength is defined by the average of the bond stresses just before slipping.

$f_B(x)$ is bond stress occurring at x and Tcfs is the tensile force occurring in the CFS at x.

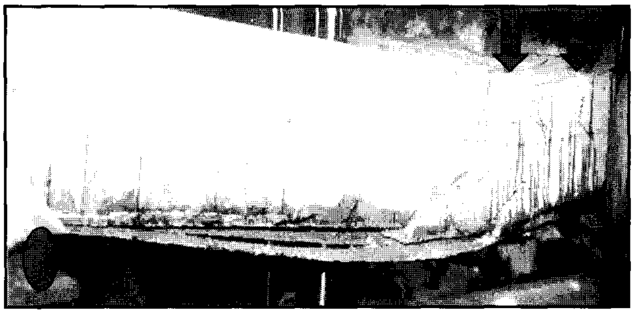


Fig. 4 Typical debonding failure

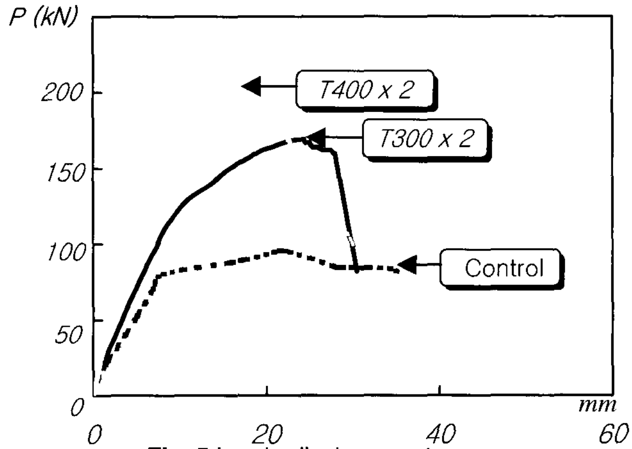


Fig. 5 Load - displacement curves

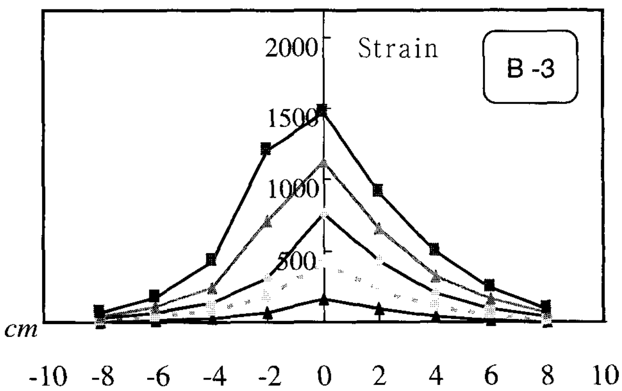


Fig. 6 Measured strain distribution at each load level

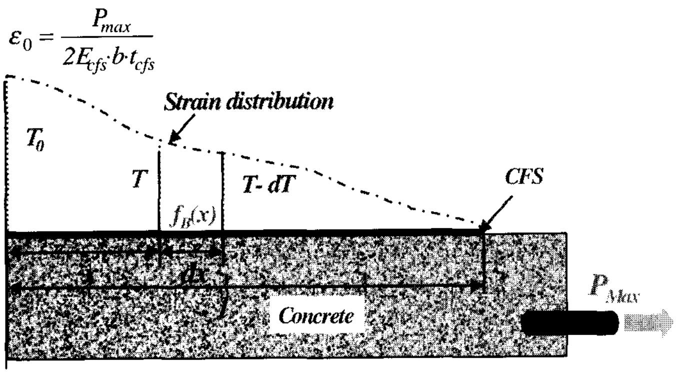


Fig. 7 Measured strain distributions just before slipping

$$T_{cfs} = E_{cfs} \cdot \varepsilon_{cfs} \cdot b \cdot t_{cfs}$$

$$dT / dx = E_{cfs} \cdot (d\varepsilon / dx) \cdot b \cdot t_{cfs} \tag{2}$$

$$dT = f_B(x) \cdot b \cdot dx$$

$$f_B(x) = (dT / dx) / b$$

Here, t_{cfs} : Thickness of CFS

Therefore, the average bond strength f_B is;

$$f_B = \int_0^l E_{cfs} \cdot t_{cfs} \left(\frac{d\varepsilon}{dx}\right) dx / l \tag{3}$$

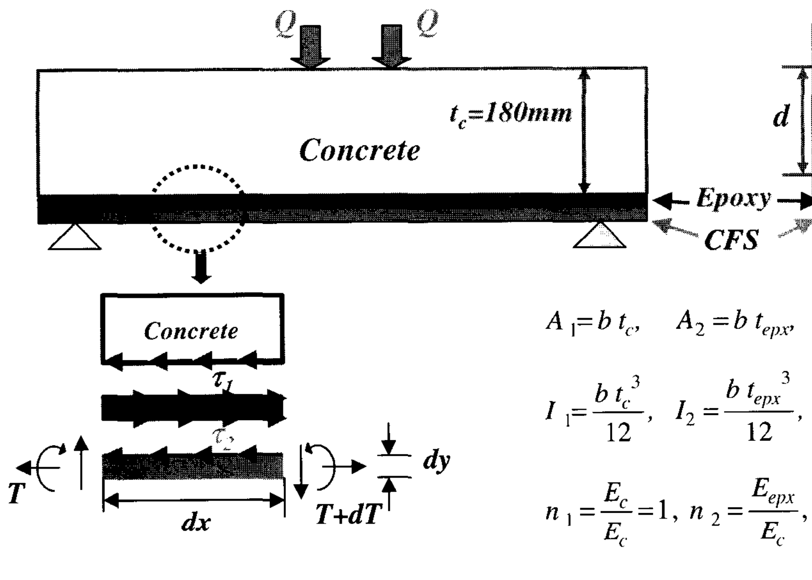
4. Estimation of the ultimate flexural strength

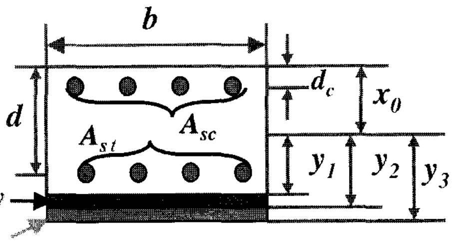
A new analytical investigation for evaluating ultimate flexural strength of a RC slab laminated by CFS is introduced. The estimation of the ultimate flexural strength of a slab was tried under the assumption that the failure occurs when the shear stress between the concrete bottom and the glued CFS reaches the bond strength. The shear stress was evaluated theoretically and the bond strength was obtained by a laboratory test as shown in Fig. 3. The ultimate flexural strength of the slabs was obtained by the flexural static test as shown in Fig. 1.

4.1 Derivation of shear stress and failure load

Debonding of CFS from concrete is actually delamination of epoxy layer from the concrete surface. The section of the test slab is divided into RC slab, epoxy resin and CFS as shown in Fig. 8.

The centroid position of the transformed composite section measured from the top of the slab is





$$A_1 = b\,t_c,\quad A_2 = b\,t_{epx},\quad A_3 = b\,t_{cfs},\quad A_{sc},\quad A_{st}$$

$$I_1 = \frac{b\,t_c^3}{12},\quad I_2 = \frac{b\,t_{epx}^3}{12},\quad I_3 = \frac{b\,t_{cfs}^3}{12},\quad I_{sc},\quad I_{st}$$

$$n_1 = \frac{E_c}{E_c} = 1,\ n_2 = \frac{E_{epx}}{E_c},\ n_3 = \frac{E_{cfs}}{E_c},\ n_{sc} = \frac{E_{sc}}{E_c},\ n_{st} = \frac{E_{st}}{E_c}$$

$$y_1 = t_c - x_0,\quad y_2 = t_c + t_{epx} - x_0,\quad y_3 = t_c + t_{epx} + t_{cfs} - x_0$$

$$d_1 = \frac{t_c}{2},\quad d_2 = t_c + \frac{t_{epx}}{2},\quad d_3 = t_c + t_{epx} + \frac{t_{cfs}}{2}$$

Where, A_i is the section area of each material (A_{sc} and A_{st} are the section area of the compressive and tensile steel), I_i is the moment of inertia of each material, x_0 is the centroid position of the composite section measured from the top of the slab, n_i is the elastic modulus ratio of each material to the concrete, d_c is the cover of the re-bar in the compression side.

Fig. 8 Analysis of composite slab

$$x_0 = \frac{n_l A_l d_1 + n_2 A_2 d_2 + n_3 A_3 d_3 + n_{sc} A_{sc} d_c + n_{st} A_{st} d}{n_l A_l + n_2 A_2 + n_3 A_3 + n_{sc} A_{sc} + n_{st} A_{st}} \quad (4)$$

The moment of inertia of the composite section I_0 is;

$$I_0 = \sum_{i=1}^{3} n_i \{I_i + (x_0 - d_i)^2 A_i\} + [n_{sc}\{I_{sc} + (x_0 - d_c)^2 A_{sc}\}] + [n_{st}\{I_{st} + (x_0 - d)^2 A_{st}\}] \quad (5)$$

The shear stress τ_1 and τ_2 mobilized between concrete and epoxy layer and between epoxy layer and CFS can be derived by considering the equilibrium conditions of an infinitesimal part dx. First, the tensile stress in the CFS is;

$$\sigma_{cfs} = n_3 \ (N/A + M/I \cdot y) \quad (6)$$

If axial force N = 0, the incremental stress of CFS in the distance dx is;

$$d\sigma_{cfs} = n_3 \ (\frac{y}{I} \cdot dM) \quad (7)$$

$$d\sigma_{cfs}/dx = n_3 \ (\frac{dM}{dx} \cdot \frac{y}{I}) = n_3 \ (\frac{Q}{I} \cdot y) \quad (8)$$

$$d\sigma_{cfs} = n_3 \ (\frac{Q}{I} \cdot y)\, dx \quad (9)$$

Therefore, the incremental tension force dT in the CFS is;

$$dT = \sigma_{cfs} \cdot dA = n_3 \int_{y2}^{y3} (\frac{Q}{I} \cdot y \cdot dx) \cdot dA \quad (10)$$

On the other hand, from the equilibrium of horizontal force;

$$dT = \tau_2 \cdot b \cdot dx \quad (11)$$

$$n_3 \int_{y2}^{y3} (\frac{Q}{I} \cdot y)\, dx \cdot dA = \tau_2 \cdot b \cdot dx \quad (12)$$

Therefore, the shear stress τ_2 between epoxy layer and CFS can be defined as follows

$$\tau_2 = \frac{Q}{Ib} [\, n_3 \int_{y2}^{y3} y dA] = \frac{Q}{I} [n_3 \int_{y2}^{y3} y dy] = \frac{n_3 Q}{2I} [y_3^2 - y_2^2] \quad (13)$$

and, the shear stress τ_1 between concrete and epoxy layer is

$$\tau_1 = \frac{Q}{Ib} [n_2 \int_{y1}^{y2} y dA + n_3 \int_{y2}^{y3} y dA] = \frac{Q}{I} [n_2 \int_{y1}^{y2} y dy + n_3 \int_{y2}^{y3} y dy] = \frac{n_2 Q}{2I} [y_2^2 - y_1^2] + \tau_2 \quad (14)$$

Where, Q is the shear force acting to the section, n_2 and n_3 are the elastic modulus ratio of epoxy resin and CFS to the concrete, respectively.

Assuming that failure of the slab occurs when $\tau_1 = f_B$ (=bond strength between concrete and CFS obtained by a laboratory test), the flexural strength of the slab in the above equation becomes

$$Q = 2 f_B I / k \quad (15)$$

Where, $k = n_2 \ \{ y_2^2 - y_1^2 \} + n_3 \{ y_3^2 - y_2^2 \}$

Neglecting t_{epx} and t_{cfs} comparing to $(t_c - x_0)$,

$$(y_2^2 - y_1^2) = (y_2 + y_1)(y_2 - y_1) = (2t_c - 2x_0 + t_{epx}) \cdot t_{epx} \approx 2(t_c - x_0) \cdot t_{epx}$$
$$(y_3^2 - y_2^2) = (2t_c - 2x_0 + t_{epx} + t_{cfs}) \cdot t_{cfs} \approx 2(t_c - x_0) \cdot t_{cfs} \quad (16)$$

and also neglecting $E_{epx} \ t_{epx}$ comparing to $E_{cfs} \ t_{cfs}$;

$$k = \frac{2(t_c - x_0)}{E_c} \{E_{epx} \cdot t_{epx} + E_{cfs} \cdot t_{cfs}\} \approx 2(t_c - x_0) \frac{E_{cfs}}{E_c} \cdot t_{cfs} \quad (17)$$

Then

$$Q = 2 f_B E_c I / (t_c - x_0) E_{cfs} \cdot t_{cfs} \quad (18)$$

Therefore, flexural failure load is

$$P = 2Q = 4 f_B E_c I / (t_c - x_0) E_{cfs} \cdot t_{cfs} \quad (19)$$

Here,

$$I = \frac{1}{3} b x_0^3 + n_{st} A_{st} (d - x_0)^2 + n_{sc} A_{sc} (x_0 - d_c)^2 + n_2 A_{epx} (t_c - x_0 + \frac{1}{2} t_{epx})^2 + n_3 A_{cfs} (t_c - x_0 + t_{epx} + \frac{1}{2} t_{cfs})^2 \quad (20)$$

Neglecting t_{epx} and t_{cfs} comparing to $(t_c - x_0)$ as before

$$I = \frac{1}{3} b x_0^3 + n_s A_{st} (d - x_0)^2 + n_s A_{sc} (x_0 - d_c)^2 + (n_2 A_{epx} + n_3 A_{cfs})(t_c - x_0)^2 \quad (21)$$

Where, n_{sc} and n_{st} are the elastic modulus ratio of compression steel and tension steel to concrete, d_c is the cover of the steel in the compression side, A_{epx} and A_{cfs} are the section area of the epoxy layer and CFS.

4.2 Evaluation of the elastic modulus of concrete by back analysis

I and x_0 are calculated on the assumption that the concrete in tension zone and yielded re-bar do not contribute to the gross section. It is however difficult to choose the approximate value for the elastic modulus of the concrete since the elastic modulus is dependent on the strain level which varies with load level and also varies from the place to place in the concrete slab.

The over-all elastic modulus of concrete at the near failure of the test slab is evaluated by comparing the flexural rigidity at the initial state $E_{co}I_o$ and at the final state E_cI both evaluated from the deflection at the span center. Where, E_{co} is the initial tangent of the concrete and I_o is the moment of inertia of the composite slab based on the gross section. E_c is called as the over-all elastic modulus of concrete in this research. Under the above assumptions, E_c does not differ from E_{co} so much as shown in Table 4. Therefore, the elastic modulus may be taken as a constant value in this analysis.

4.3 Comparison of theoretical and experimental results

Bond strength f_B between concrete and CFS (actually epoxy layer) was conducted by a laboratory test and evaluated by two methods as shown in Table 5. Only two specimens were tested for each case and the gap of these two data was large. The theoretically obtained ultimate flexural strength was compared with the test result. Table 6 shows the comparison of the calculated strength with the corresponding experimental result. The corresponding average bond strength was used in the evaluation of the flexural strength. From the results, it is found that this new method gives a relatively good estimate of the ultimate flexural strength of the composite slab. The gap between the calculated value P_{cal} and the corresponding experimental value P_{exp} is considered to arise mainly from the unsatisfactory evaluation of the bond strength f_B.

5. Conclusions

A proposed analytical method based on bond strength between concrete and CFS to evaluate the flexural strength of RC slab strengthened with CFS was discussed. The following conclusions can be drawn;

(1) The proposed method to evaluate the flexural strength of a RC member strengthened by CFS is expected to give a good estimate of the ultimate strength. It is found in this study, however that the evaluation of the bond strength between concrete and CFS is the key and that the evaluation of the moment of inertia of the composite section in which concrete being cracked and the re-bar being yielded is also the key. The accuracy of the thickness and the elastic modulus of CFS are also influential.

(2) Further research concerning the new failure modes such as delamination of CFS, evaluation of bond strength and retrofit design methodologies must be studied to clarify the mechanical behavior of laminated composite member and to assure safe practical application in construction site.

Table 4 Experimental test results of slab specimens

CFS 2 layers	Test slab	E_{co} (N/mm^2) ×10^4	E_c (N/mm^2) ×10^4	I_0 (cm^4)	I (cm^4)	x_0 (cm)	P_{exp} *(kN)*
T300	S-1	2.90	2.78	20920	2950	3.44	157.8
	S-2	2.95	2.53	20860	3230	3.57	165.6
T400	S-3	3.30	3.08	20790	3940	3.80	198.0

Table 5 Bond strength f_B *(N/mm^2)*

CFS 2 layers	f_B by the Method 1			f_B by the Method 2		
	Specimen *No.1*	Specimen *No.2*	***Average bond strength***	Specimen *No.1*	Specimen *No.2*	***Average bond strength***
T300	1.69	1.23	***1.46***	1.62	1.14	***1.38***
T400	2.16	1.89	***2.03***	1.63	1.38	***1.51***

Table 6 Comparison of the calculated and experimental results on flexural strength

CFS 2 layers	Test slab	P_{cal} / P_{exp} *(f_B by the Method 1)*			P_{cal} / P_{exp} *(f_B by the Method 2)*		
		f_B *-No.1*	f_B *–No.2*	f_B ***-ave***	f_B *-No.1*	f_B *–No.2*	f_B ***-ave***
T300	S-1	1.46	1.06	***1.26***	1.40	0.98	***1.18***
	S-2	1.38	1.0	***1.20***	1.32	0.93	***1.13***
T400	S-3	1.41	1.24	***1.32***	1.07	0.90	***0.99***

REFERENCES

1. An W., Saadatmanesh, H., and Ehsani, M.R., "RC Beams Strengthened with GFRP Plates. II: Analysis and Parametric study," *ASCE, Journal of Structural Engineering*, Vol.117, No.11, 1991, pp.3434-3455.
2. Arduini, M., et al., "Behavior of Pre-cracked RC Beams Strengthened with Carbon Fiber Sheets," ASCE, Journal of Composites for Construction, Vol.1, No.2, May, 1997, pp.63-70.
3. Buyukozturk, O. and Hearing, B., "Failure Behavior of Precracked Concrete Beams Retrofitted with FRP," *ASCE, Journal of Composites for Construction*, Vol.2, No.3, 1998, pp.138-144.
4. Malek A, M. and Saadatmanesh, H., 1998, "Analytical Study of Reinforced Concrete Beams Strengthened with Web-Bonded Fiber Reinforced Plastic Plates or Fabrics," *ACI Structural Journal*, Vol.95, No.3, May-June, pp.343-352.
5. Robert, T. M., "Approximate Analysis of Shear and Normal stress Concentrations in the adhesive layer of Plated RC Beams," *Magazine of Concrete Research*, Vol.48, No.12/20, 1989, pp.229-233.
6. Chajes, M. J. and et al., "Bond and Force Transfer of Composite Material Plate Bonded to Concrete," *ACI Structural Journal*, Vol.93, No.2, 1996, pp.208-217.
7. Täljsten, B., "Strengthening of Beams by Plate Bonding," *ASCE, Journal of Materials in Civil Engineering*, Nov., 1997, pp.206-212.
8. Sato, Y., et al., 1997, "Bond Behavior between CFRP Sheet and Concrete (Part 1),"AIJ, Journal of Struct. Constr. Eng, No.500, Oct, pp.75-82.
9. Park, H., G. and Ono, K., "Interfacial Bond Behavior Between Concrete Surface and Carbon Fiber Sheet," *Proceedings of the 12th KU-KAIST-NTU-NUS Seminar on Civil Engineering, Korea*, 1999, pp.141-146.
10. Park, H. G. and Ono, K., "Strength Evaluation of RC Slab Strengthened by Carbon Fiber Sheet," *Proceedings of the 8th International conference and Exhibition*, Structural Faults & Repair-99, London, CD-ROM, 1999.
11. Park, H., G., "*Mechanical Behavior of Reinforced Concrete Slab Retrofitted with Carbon Fiber Sheet*," Ph.D. Dissertation, Kyoto university, Japan, March, 2000, pp.97~114.