Journal of the Korea Concrete Institute
Vol.17 No.1, pp.149~155, February, 2005

Effect of Multi-Layer Carbon Fiber Sheet Used for Strengthening Reinforced Concrete Beams

Young-Chan You[1)]*, Ki-Sun Choi[1)], and Keung-Hwan Kim[1)]

[1)]*Building Research Division, Korea Institute of Construction Technology, Korea*

(Received February 5, 2004; Accepted December 31, 2004)

Abstract

The purpose of this study is to investigate the flexural strengthening effects of CF(Carbon Fiber) sheet for the full-scale RC beams with multi-layer CF sheets. The partial strength reduction factors of CF sheets are suggested from the full-scale RC beams tests strengthened with multi-layer CF sheets up to six layers as well as material tests. From the material tensile tests, it was observed that the average tensile strengths of CF sheets per layer are decreased as the number of CF sheets is increased. Also the steep strength reductions of CF sheets in material test results at rupture are observed compared with the structural tests results for the full-scale RC beams strengthened with multi-layer CF sheets. Finally, the partial strength reduction factors for CF sheets up to six layers are suggested considering the effects of multi-layer and unit weight of CF sheets.

Keywords : ***CF(carbon fiber) sheet, CFRP(carbon fiber reinforced polymer), partial strength reduction factor, design strength, multi-layer***

1. Introduction

CF(Carbon Fiber) sheet is considered to be the alternatives to the steel plate due to the high strength, high stiffness, lower weight and the excellent resistance against fatigue. The specified tensile strength provided by the manufacturer is determined on the basis of the reliable strength lower limit ($X-3\sigma$: X=average tensile strength, σ=standard deviation) obtained from the material tests.[7,8)] Most of these data, however, are based on the test results of 1 layer of CF sheet. Also, some researchers[1,2)] suggested the partial strength reduction factor for strengthening RC members with CFS system based on the small-scale model tests. But, in the case of small-scale model tests, the number of CF sheets is usually limited within 2 layers due to the geometrical restrictions. When the number of CF sheets becomes 3 or more, the final failure modes of the small-scale member were governed by the debonding of CF sheets or the compression failure of concrete, causing under-estimation of the strengthening effects of CF sheets.[5)]

On the other hand, CFRP(Carbon Fiber Reinforced Polymer) consists of CF sheets and the saturating epoxy resin which impregnates and bonds CF sheets to the concrete. So, the accumulated partial defects of saturating epoxy and irregular arrangement of carbon fiber can cause the reduction of tensile strength of CFRP as the number of CF sheets increases. The objective of this study is to investigate the strength reduction characteristics of multi-layer CF sheets up to 6 through the full-scale model tests as well as the material tests.

2. Experimental program

2.1 Material tests

Air-entrained concrete with specified compressive strength of 24 MPa was supplied by a local ready-mix plant. Type I portland cement and 25 mm nominal maximum size coarse aggregate were used. Compression cylinders measuring φ100×200 mm are prepared for each specimen. The material test for high strength 200g/m^2 and 300g/m^2 CF sheets produced by domestic manufacturer in Korea were carried out. Tensile properties as well as me-

* *Corresponding author*
E-mail address: ycyou@kict.re.kr

chanical properties of CF sheets and epoxy resin were obtained. The material tests for the multi-layer CF sheets were carried out according to the standard test procedure of JIS K 7073[6] using U.T.M whose permissible capacity is 50 kN. The width and length of tensile test specimen are 12.5mm and 200mm, respectively. Also, GFRP taps with 1.5mm thickness were attached at each end of test specimen. Table 1~4 show the test results of the each materials.

Material test specimen of CF sheets ranged from 1 to 5 layers for HS200 and from 1 to 3 layers for HS300. In this study, 'HS' and the number after 'HS' stand for high strength and fiber weight per unit square meters in gram, respectively. The fiber thickness of single layer of HS300 is 1.5 times thicker than that of HS200.

2.2 Full-scale RC beam tests

2.2.1 Test specimen

The full-scale RC beam specimens were manufactured in order to ensure the sufficient bonding length of CF sheets up to 6 layers. On the other hands, according to the sectional analysis for the rectangular RC beam strengthened with more than 3 layers of HS200 CF sheets, the compression failure of concrete at the extreme compressive fiber of concrete preceded the rupture of CF sheets at the extreme tensile fiber of concrete. Consequently, T beam with effective width of slab were manufactured in the case of the specimen strengthened by 4 or 6 layers of HS200 CF sheets and by 3 layers of HS300 CF sheets in order to provide sufficient compressive block and to prevent the compression failure of the strengthened members.

At all the strengthened specimens, 'U-shape fiber wrap' as shown in Fig. 1 were applied at the nearby loading point which was proved to have the feasibility to prevent the debonding failure of CF sheets caused by the large flexural-shear deformation.[5] The details and dimensions of test specimens are shown in Fig. 1 and Table 5.

Table 1 Material properties of concrete

Curing age	Tensile strength (MPa)	Compressive strength(MPa)	Young's modulus(GPa)
69 days	3.25	35.2	28.1

Table 2 Material properties of reinforcing bar

Bar size	Yield strength (MPa)	Young's modulus(GPa)	Tensile strength(MPa)	Elongation (%)
D10	390.1	176	562.0	28
D19	406.1	179	626.2	19
D22	361.0	171	565.8	17

Table 3 Material properties of CFRP (t_{cf}=0.111mm)

Classification	Tensile strength (MPa)	Young's modulus (GPa)	Failure strain (%)
Nominal	3,550	235.0	1.51
Test	4,513	259.0	1.70

Table 4 Material properties of epoxy resin

Classification	Compressive strength(MPa)	Tensile strength(MPa)	Flexural strength (MPa)	Shear strength (MPa)
Nominal	70.0	30.0	40.0	10.0
Test	64.7	32.0	49.0	11.0

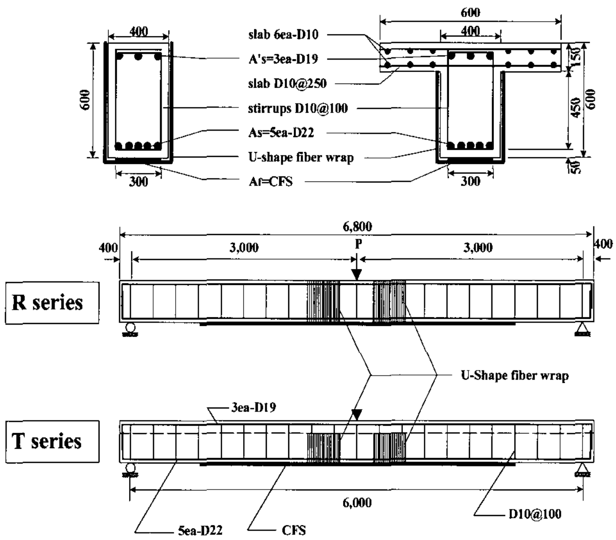


Fig. 1 Details and dimension of typical specimens

Table 5 Details of reinforcing bar and CF sheets

Specimen	Reinforcement	Layer (ply)	Bond length(mm)	Remark
RS	A'_s= 861 mm^2	-	-	Control
RF1-UCS3	A_s=1,935 mm^2	1	2,000	HS300
RF2-UCS3	ρ/ρ_b=0.3	2	4,000	HS300
RF2-B2		2	2,700	HS200
TS	A'_s= 861 mm^2	-	-	Control
TF3-UCS3	A_s=1,935 mm^2	3	6,000	HS300
TF4-UCB2	ρ/ρ_b=0.17	4	5,400	HS200
TF6-UCB2		6	6,000	HS200

A'_s : area of top bar
A_s : area of bottom bar
ρ : reinforcement ratio
ρ_b : reinforcement ratio at balanced failure

2.2.2 Test set-up

The loading frame at which 1-point load is applied at the center of beam specimen was set-up for the structural test whose permissible capacity is 1000 kN(Fig. 2). As a measuring device, two units of 200mm LVDT were settled for the measurement of deflection at mid-span. Ten units of strain gauge type transducer (PI Displacement Transducer) were settled at 60mm intervals at central part of the beam to obtain the sectional strain gradient. Two units of WSG(wire strain gauges) were settled on the central part of lower CFS. For the specimen with U-shape fiber wrap, the WSG were attached on the U-wrap along the fiber direction to measure the CF sheets strain. Fig. 4 shows the location of the each measuring apparatus.

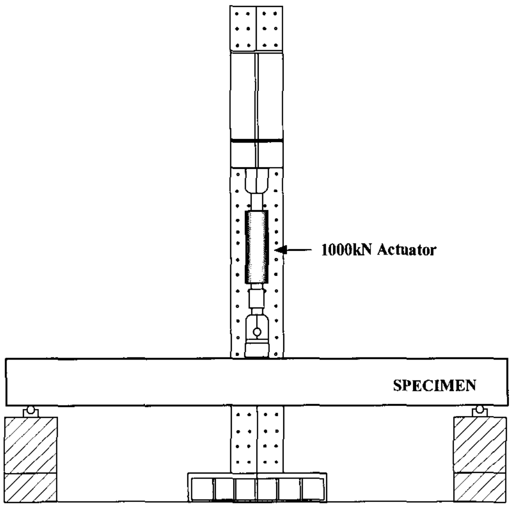


Fig. 2 Specimen test set-up

3. Test results

3.1 Material test results

Table 6 shows the material tensile test results for HS200 and HS300 CF sheets. As shown in Table 6, it is clear that the tensile strength of CF sheets is decreased as the number of CF sheets is increased in the material test results.

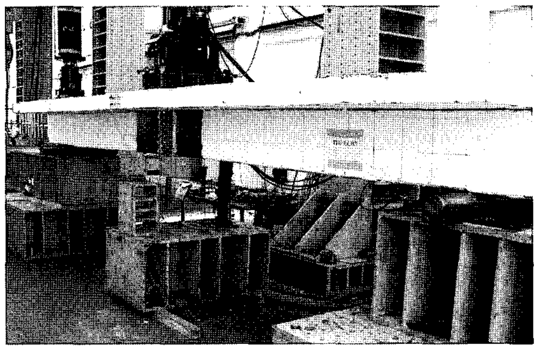


Fig. 3 General view of test set-up

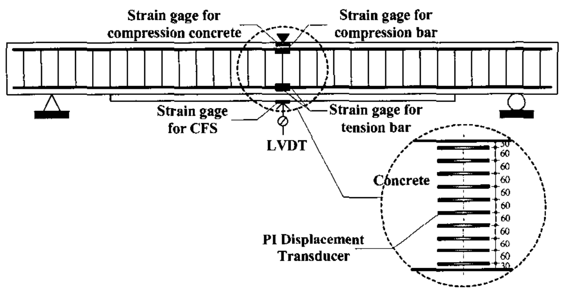
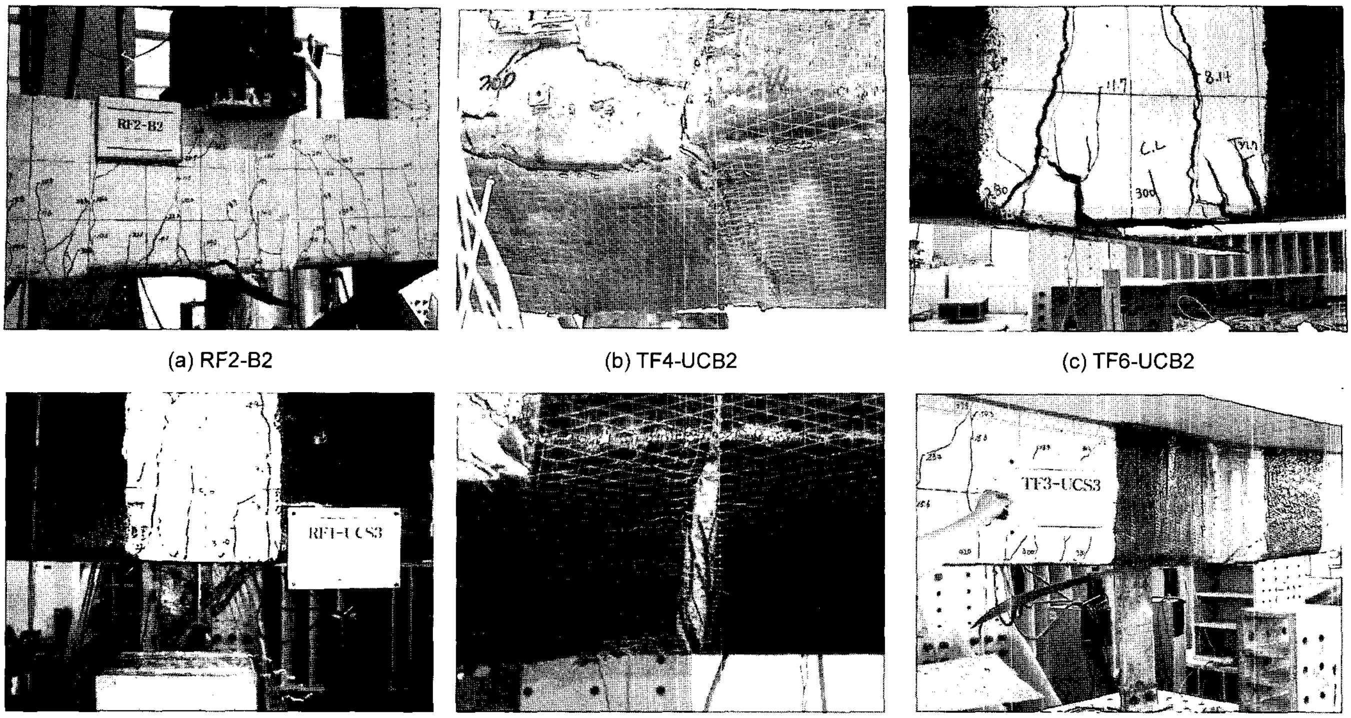


Fig. 4 Location of measurement apparatus

Table 6 Material tensile strength and reliable lower limits

CF Type	Layer	CF THK(mm)	Section Area(mm^2)	Max. Load(kN)	Tensile Strength(MPa)	X-3σ_n(MPa)
200g	1-ply	0.111	1.34	6.04	4,477(1.00)*	3,954
	2-ply	0.222	2.70	11.03	4,072(0.91)*	3,451
	3-ply	0.333	4.09	15.17	3,707(0.83)*	3,189
	4-ply	0.444	5.33	19.07	3,581(0.80)*	3,124
	5-ply	0.555	6.95	24.83	3,572(0.79)*	2,779
300g	1-ply	0.167	2.06	8.99	4,367(1.00)*	3,533
	2-ply	0.334	4.11	15.62	3,803(0.87)*	3,240
	3-ply	0.501	6.47	24.48	3,784(0.86)*	3,201

* The number in a parenthesis represent the tensile strength ratio of each specimen compared to that of 1-ply specimen
X : average tensile strength
σ_n : standard deviation



(a) RF2-B2 (b) TF4-UCB2 (c) TF6-UCB2

(d) RF1-UCS3 (e) RF2-UCS3 (f) TF3-UCS3

Fig. 5 Final failure pattern : (a) ~ (f) CF sheets rupture

Although all the average tensile strength of CF sheets per layer exceed the nominal tensile strength, the reliable strength lower limit of CF sheets considering large strength deviation of CF sheets, X-3σ_n, is less than the specified nominal tensile strength as shown in Table 6.

3.2 Full-scale RC beam test results

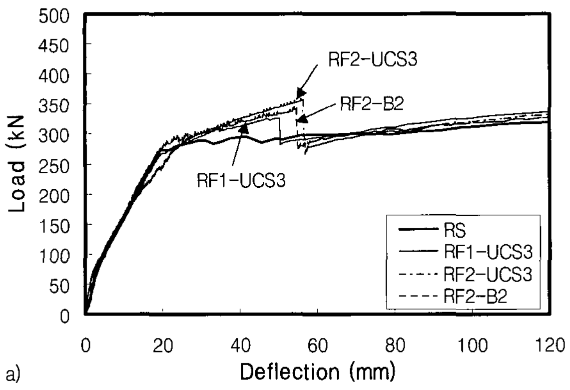
3.2.1 Failure mode

Fig. 5 and Table 7 show the final failure modes and the test results of each specimen, respectively. Here, ΔP_{cf} in Table 7 indicates the difference between the maximum load of strengthened specimens and the yield load of control beam. The failure mode of all the specimen were governed by the rupture of CF sheets regardless of fiber type and the number of layers even though local debonding was observed between concrete and CF sheets after the tensile reinforcements were yielded. But the rupture strain of CF sheets at each specimen varied from 6,998×10^{-6} to 12,395×10^{-6}, that is 46~82% of the specified rupture strain. Fig. 6 represents the load-deflection relationship of each specimen at mid-span.

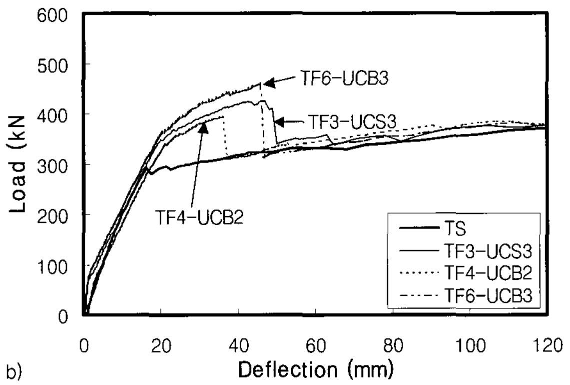
Table 7 Comparison of calculated and experimental results

Specimen	Yield load(kN)		Max. load(kN)			ΔP_{cf} (kN)	δ (mm)	ε_c (×10^{-6})	ε_{cf} (×10^{-6})	Failure mode
	Cal_n	Exp	Cal_n	Cal_u	Exp					
RS	252.6	284.5	264.7	299.5	312.7	-	76.90	3,000	-	Flexural
RF1-UCS3	261.6	269.9	327.9	356.2	340.2	55.7	50.19	2,587	12,395	CF sheet rupture
RF2-UCS3	270.3	277.0	390.0	416.0	372.0	87.5	56.20	-	10,423	"
RF2-B2	264.4	284.8	346.8	378.0	357.1	72.6	54.12	2,755	9,796	"
TS	264.6	303.8	277.8	315.2	404.7	-	16.34	843	-	Flexural
TF3-UCS3	291.6	358.4	475.5	586.3	443.1	139.3	48.93	1,390	7,730	CF sheet rupture
TF4-UCB2	288.5	349.5	452.7	557.4	410.7	106.9	36.02	1,315	6,998	"
TF6-UCB2	300.6	375.4	540.9	669.1	478.5	174.7	45.72	1,666	7,436	"

Cal_n : Nominal yield load
Cal_u : Nominal ultimate load with actual material strength
ε_c : Concrete strain at CF sheets rupture (Ultimate state)
Cal_n : Nominal ultimate load with nominal material strength
ΔP_{cf} : Load decrease at CF sheet rupture
ε_{cf} : CF sheet strain at CF sheet rupture (Ultimate state)

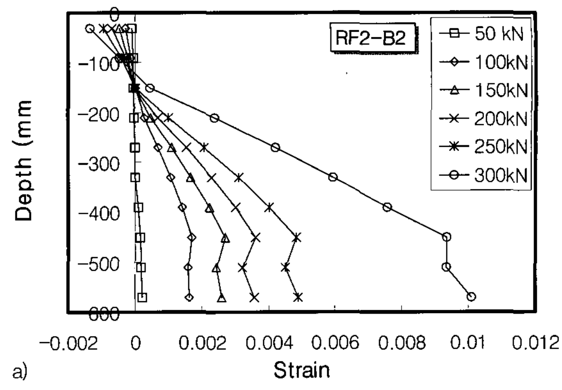


(a) Rectangular section

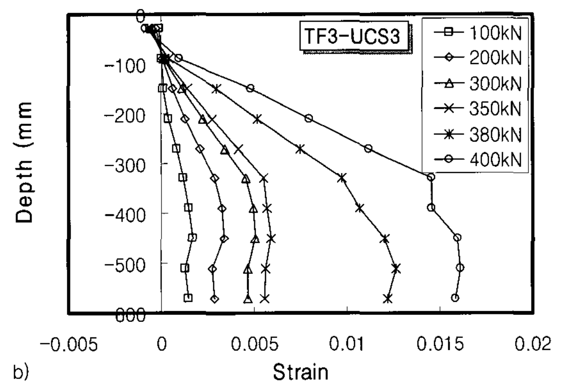


(b) T-section

Fig. 6 Load-deflection curves



(a) RF2-B2



(b) TF3-UCS3

Fig. 7 Sectional strain gradients

3.2.2 Sectional strain gradient

Fig. 7 shows the sectional strain gradient obtained from ten units of PI Displacement Transducers which were settled at 60mm intervals on the beam web as shown in Fig. 4. The sectional strain distribution appears to be a linear before yielding of reinforcing bar, but strain of reinforcing bar tends to be greater than that of CFS after yielding. It means that some slips are expected to be happened between concrete tensile fiber and CFS. From that point of view, an actual distance from extreme compression fiber to neutral axis is always smaller than that theoretically computed by linear strain distribution, which results in conservative estimations.

3.2.3 Strengthening effects by CFS

Previous studies[1-4] estimated the strengthening effects of FRP on the basis of the strength increments between the nominal flexural capacity of non-strengthened members by analysis and the maximum flexural capacity of strengthened members by test. But this method has the possibilities to overestimate the strengthening effects by CFS because probable strength increment of RC members was included in the maximum flexural capacity of the strengthened beams.

For this reason, we apply the processes as shown in (a)~(d) to obtain the real strength increments by the CFS strengthening. The process of calculation is as follows.

(a) Calculate the strength increment (ΔP_{cf}) between the maximum load(P_u) and the decreased load (P_s) at CFS rupture.
(b) Calculate the moment increment (ΔM_{cf}) from (a).
(c) Calculate the tensile stress (f_{cf}) at CFS rupture by sectional analysis.
(d) Calculate the strain ($\varepsilon_{cf\text{-}cal}$) by dividing the tensile stress of (c) by the elasticity modulus of CFS.

The calculated characteristic values by the procedures mentioned above are shown in Table 8. As shown in Table 8, the ultimate strains calculated following this procedure are almost similar to the measured strains of each specimen. Thus, all the measured data and the test method for strengthening effects by CFRP are considered very reliable.

3.2.4 Partial strength reduction factor

The tensile strengths of multi-layer CFS at rupture are shown in Figs. 8 and 9 obtained from the full-scale RC beam tests as well as the material tests. As shown in Figs. 8

and 9, the tensile strengths of CFS at rupture were decreased generally as the number of layers was increased. The declining rate is also reduced and converges to a certain value. On the other hands as shown in Fig 9, the tensile strength declining rate of HS300 CFS at rupture doesn't converge to a certain value. However, there is little possibility to be strengthened by more than 3 layers of HS300 CFS, the test results within this limit will be sufficient to understand the strength declining rate of CFS.

The HS300 CFS was reported to have the same physical properties compared with those of the HS200 CFS except the fiber thickness is 0.167mm, which is about 1.5 times that of HS200 CFS. However, according to the test results, the tensile strength of HS300 CFS was less than that of the HS200 CFS at the same number of layer. It indicates that the strength reduction characteristics can be varied not only by the number of layer but also by the fiber weight per unit area. Thus the simple assumption that the tensile strength of HS300 CFS is 1.5 times higher than that of HS200 CFS must be reviewed.

As shown in Figs. 8 and 9, the tensile strengths of multi-layer CFS at rupture were decreased linearly as the number of CFS layer was increased and converge to a certain value. These strength reduction characteristics for the multi-layer CFS can be denoted as follows based on the linear regression analysis obtained from the full-scale RC model tests.

$$\Psi = \Phi - (n-1)\times 0.11 \geq 0.5 \quad (1)$$

Where, Ψ: partial strength reduction factor of CFS

Φ: initial value by different fiber weight (HS200=0.83, HS300=0.70)

n : the number of CFS layer

The tensile strengths of the multi-layer CFS observed in

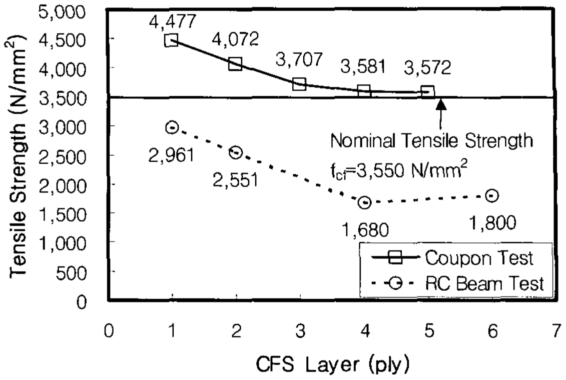


Fig. 8 Tensile strength of the multi-layer HS200 CF sheets

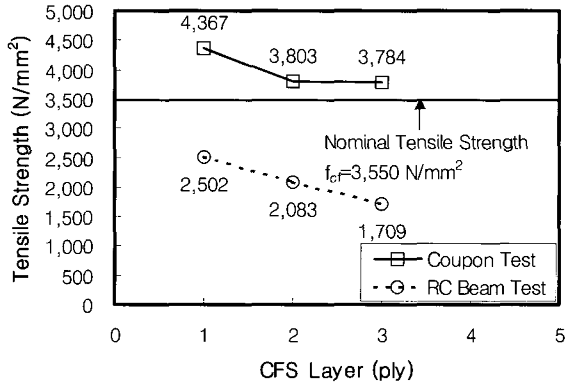


Fig. 9 Tensile strength of the multi-layer HS300 CF sheets

all the strengthened specimens are quite less than the specified tensile strength by manufactures, f_{cfn}=3,550 N/mm^2. The ACI Committee 440 recommends the partial strength reduction factor as 0.85 for the flexural members and AIK (Architectural Institute of Korea) recommends the strength reduction factor as 0.7. But they seem to overestimate the

Table 8 Tensile stress and measured strain of CF sheets

Specimen	Layer(ply)	P_u(kN)	P_s(kN)	ΔP_{cf}(kN)	ΔM_{cf}(kN·m)	ΔT_{cf}(kN)	f_{cf}(MPa)	$\varepsilon_{cf\text{-}cal}(\mu)$	$\varepsilon_{cf\text{-}sg}(\mu)$	f_{cf}/f_{cfn}
RF2-B2	2	357.1	294.0	63.1	94.7	169.9	2,551	10,856	9,796	0.72
TF4-UCB2	4	410.7	325.1	85.6	128.4	223.8	1,680	7,150	6,998	0.47
TF6-UCB3	6	478.5	341.6	136.9	205.4	359.6	1,800	7,659	7,436	0.51
RF1-UCS3	1	340.2	293.5	46.7	70.1	125.4	2,502	10,647	12,395	0.70
RF2-UCS3	2	372.0	295.0	77.0	115.5	208.7	2,083	8,862	10,423	0.59
TF3-UCS3	3	443.1	345.0	98.1	147.2	256.8	1,709	7,271	7,730	0.48

P_u : Maximum load before CFS rupture
P_s : Decreased load after CFS rupture
ΔP_{cf} : Load difference before and after CFS rupture
ΔM_{cf} : Moment difference before and after CFS rupture
T_{cf} : Tensile force of CFS calculated as $\Delta M_{cf}/Z$
f_{cf} : Tensile stress of CFS calculated as T_{cf}/A_f
$\varepsilon_{cf\text{-}cal}$: Tensile strain of CFS calculated as f_{cf}/E_f
$\varepsilon_{cf\text{-}sg}$: Tensile strain of CFS measured in the specimen

tensile strength of the multi-layer CFS in the case of being strengthened by 3 layers or more. Therefore, to ensure the safety of strengthened members by the multi-layer CFS, it is needed to review the partial strength reduction factor for the multi-layer CFS. The partial strength reduction factor suggested in this study can be used as the strength reduction factor of multi-layer CFS.

4. Conclusions

The strength reduction characteristics of multi-layer CFS were investigated through the material and structural tests in this study. Based on the test results, the following conclusions were drawn.

1) The tensile strength of CFS at rupture has the tendency to be decreased as the number of layer was increased in both cases of HS200 and HS300 CFS.
2) The strength reduction characteristics can be varied not only by the number of layer but also by the fiber weight per unit area.
3) The tensile strengths of CFS at rupture obtained from the full-scale model tests are remarkably less than the specified tensile strength by manufactures compared with the nominal tensile strength obtained from material test.
4) The partial strength reduction factors are suggested in this study considering the number of multi-layer CFS and fiber weight per unit area.

Acknowledgement

This paper is a part of the research project named "Performance Evaluation of Repairing and Strengthening for RC Building Structure." Support for this research by '99 National R&D Program for Construction Technology under Grant No. R&D/99-building07 is greatly acknowledged.

References

1. Sin, S.-W., "Effect of anchorage type of CFS on flexural behavior of RC beam ", *Journal of Korea institute for Structural Maintenance Inspection*, Vol.2 No.2, 1998, pp.202~208.
2. Lee, Y.-T., "Improvement of flexural capacity of reinforced concrete beams reinforced by CFS," *Journal of Korea institute for Structural Maintenance Inspection*, Vol.3 No.3, 1999, pp.203~211.
3. Lee, H.-S., "Strength of material of CFS," *Journal of Korea Concrete Institute*, Vol. 10 No.2, 1998, pp.803~808.
4. Architectural Institute of Korea, "*Repairing and strengthening of concrete structure*," Technical Report ATR 97-1, 1997, pp.127~131.
5. You, Y.-C., Kim, K.-H., Choi, K.-S., "*Performance Evaluation of Repair and Strengthening for RC Building Structure*," Korea Institute of Construction Technology, 2001, pp.220~261.
6. 建築研究振興協會, "炭素繊維シ-ト補强工事の材料と工法", 建築研究振興協會, 1997, pp.23~26.
7. 日本コンクリ-ト工學協會, "炭素繊維シ-トによるコンクリ-ト構造物の補 修·補强設計·施工マニュアル(案) 橋脚編", 連續繊維補强コンクリ-ト研究委員會報告集, 1997, pp.122~124.
8. ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP System for Strengthening Concrete Structure," American Concrete Institute, 2002, pp.21~25.