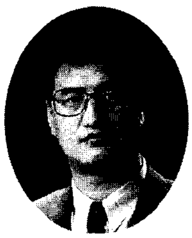
Flexural Behavior of RC Beams Strengthened with Steel Plates/Carbon Fiber Sheets(CFS) under Pre-Loading Conditions



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ABSTRACT

The reinforced concrete(RC) flexural members strengthened with steel plate/CFS at soffit have initial stresses and strains in reinforcements and concrete caused by the service loads at the time of retrofitting works. These initial residual stresses and strains of strengthened beams may affect the flexural performance of the rehabilitated beams.

The objective of this study is to evaluate and verify the effectiveness of rehabilitation by external bonded steel plates and CFS to the tension face of the beams under three conditions of pre-loading. Thirteen beam specimens are tested and analyzed. Main test parameters are pre-loading conditions, strengthening materials and reinforcement ratio of specimens. The effect of test parameters on the strengthened beams is analyzed from the maximum load capacity, load-deflection relationship, state of stress of the materials, crack propagation phase, and failure modes. Both test results and design formulas of ACI Code provisions are compared and evaluated.

Keywords : pre-loading, strengthening, flexural performance, carbon fiber sheet (CFS),steel plate

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1. Introduction

In recent years, the repair and retrofit of existing reinforced concrete(RC) structures have been important challenges to the architectural engineers. The primary reasons for strengthening of existing RC flexural members include upgrading of resistance to withstand underestimated loads, increasing the load capacity for higher allowable loads and restoring load capacity due to degradation caused by corrosion and aging.

For RC beams, flexural and shear strengthening have been achieved by epoxy bonded steel plates or carbon fiber sheets (CFS) to the soffit and the web of the beams.

Many researches are recently carried out to investigate the effect of retrofitting methods and materials on the behavior of strengthened members. From the previous researches, the effectiveness and variety of failure modes of epoxy bonding steel plates or CFS have been identified. However, there are few researches on the strengthening of RC beams in which the effect of loading conditions at the time of strengthening works is considered. The strengthened flexural members have initial stresses and strains caused by the service loads at the time of retrofitting works. These initial residual stresses and strains of the strengthened beams may affect the flexural performance of the member after rehabilitation.

This paper presents the results of experimental studies concerning the flexural strengthening of reinforced concrete beams by external bonded steel plates and CFS to the tension face of the beams under three pre-loading conditions. Also in this study, the effect of pre-loading, strengthening materials, and reinforcement ratio on the beam strength enhancement and its effect on the behavior of the beam are presented.

2. Experimental Program

2.1 Specimens

In order to analyze the effect of pre-loading conditions at the time of strengthening, thirteen beams were cast for experiments. All beams have the same dimensions, 15cm wide, 25cm high and 280cm long. Three test parameters, magnitude of pre-loading, strengthening materials, and reinforcement ratio, were used in this study. The pre-loading conditions as main test parameters of this

Table 1 Composition of specimens

Description	Dimensions (cm)	Main Bars	Compression Bars	Strengthening Materials	Pre-loading (tonf)	Remarks
CONTROL	15×25×280	2-D13	2-D10	NONE	0	unloading
CF3-CON	15×25×280	2-D13	2-D10	CFS 2 ply	0	unloading
CF3-LL	15×25×280	2-D13	2-D10	CFS 2 ply	2.17	loading
CF3-HL	15×25×280	2-D13	2-D10	CFS 2 ply	2.89	loading
CF6-CON	15×25×280	3-D13	2-D10	CFS 2 ply	0	unloading
CF6-LL	15×25×280	3-D13	2-D10	CFS 2 ply	2.13	loading
CF6-HL	15×25×280	3-D13	2-D10	CFS 2 ply	2.83	loading
SP3-CON	15×25×280	2-D13	2-D10	steel plate	0	unloading
SP3-LL	15×25×280	2-D13	2-D10	steel plate	2.14	loading
SP3-HL	15×25×280	2-D13	2-D10	steel plate	2.95	loading
SP6-CON	15×25×280	3-D13	2-D10	steel plate	0	unloading
SP6-LL	15×25×280	3-D13	2-D10	steel plate	2.13	loading
SP6-HL	15×25×280	3-D13	2-D10	steel plate	2.92	loading

study are assumed to be 0%, 50%, 70% of the nominal flexural strength of the CONTROL beams before strengthening. Strengthening materials designed under maximum reinforcement ratio. Test specimens are summarized in Table 1.

2.2 Materials

In this study, the compressive strength of concrete is about 181kgf/cm^2 since it is likely that the test results would be applied for rehabilitation of existing RC structures in the future. It needs to be noted that the domestic construction practices in the past decades were used relatively low strength structural concrete. The material properties of strengthening materials are presented in Table 2.

2.3 Test Procedure

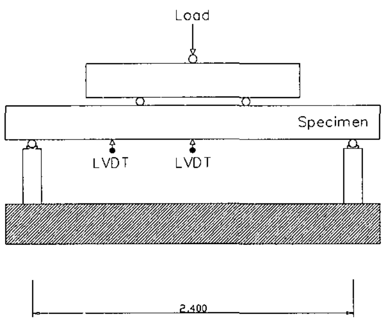
The overall test arrangement is shown in Fig. 1. The test beams were simply supported with third-point loading. To maintain the load at the time of retrofitting work, oil jack with safety nut was used as loading equipment. Displacements at the center and 1/4 point of span were measured. For measuring curvature during the test, gauges and points were used at upper and lower points of the beam section in middle of the span. Electric strain gages were used to measure strains of reinforcement, concrete and strengthening materials.

Test period took a week per specimen. Test procedures were as follows; first, test beam was installed in test device, and preloaded up to planned load. After then the loads were fixed by safety nut in loading system, retrofitting works were applied. After curing about five or six days, test was continued to the failure of the beams.

3. Results and Discussion

3.1 Effect of Pre-Loading

Ultimate moments of the test specimens are shown in Table 3. From Table 3, increasing



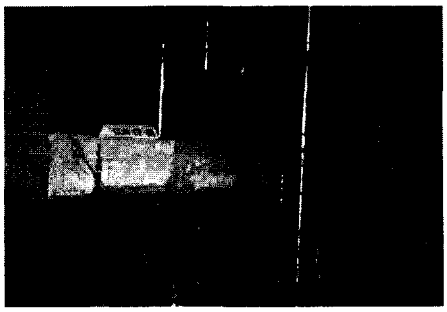
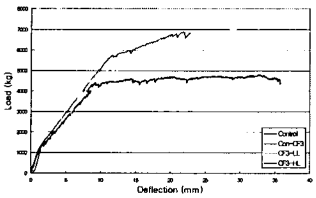


Fig. 1 Test configuration

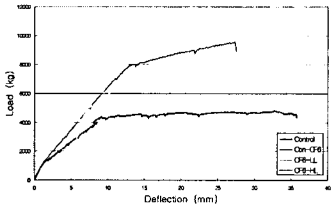
Table 2 Material properties

Description	Concrete	Carbon Fiber Sheet (CFS)	Steel Plate
Design Strength (kgf/cm^2)	181	11,800 (⅓ f_t)	2,400 (f_y)
Elastic Modulus (kgf/cm^2)	2.02 × 10^5	2.35 × 10^6	1.80 × 10^6
Others	-	0.165 mm thick	3 mm thick

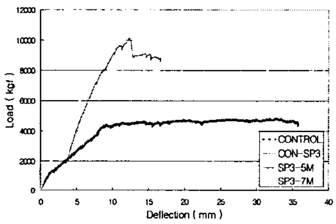
pre-loads result in decreasing ultimate moments of the beams strengthened with CFS



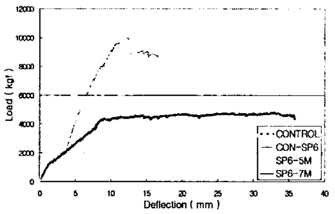
(a) CF3 series



(b) CF6 series



(c) SP3 series



(d) SP6 series

Fig. 2 Load-deflection relationships

These results indicate that pre-loading state may affect the flexural behavior of strengthened beams. It is identified from the slope changes in Fig. 2 that the increase of pre-loads decreases the yielding load of beams. It can be explained that the high pre-loads induce large pre-strains of the reinforcement in Fig. 3 and Fig. 4 and large pre-strains result in the low yielding loads of specimens.

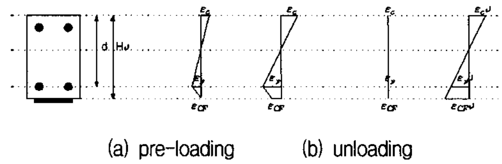
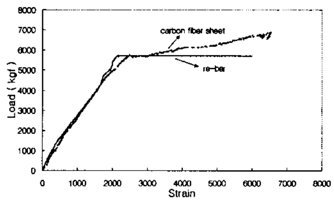
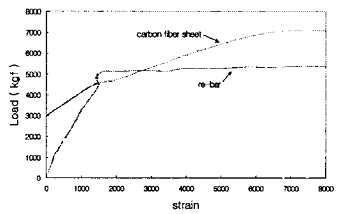


Fig. 3 Strain analysis of re-bar and strengthening materials



(a) CF3-CON



(b) CF3-HL

Fig. 4 Load-strain relationships in test

The ultimate moments of beams strengthened with steel plate increase as pre-loads increase. From failure modes and strain analysis, the test beams strengthened with CFS seem to fail after reinforcement yielding. However, the test beams strengthened with steel plate fail before reinforcement yielding. As shown on Table 4, the strain of reinforcement of most specimens with steel plate does not reach yielding strain at ultimate load. From the strain analysis and failure modes, the failure is proved to be induced from bond failure between concrete and steel plate before reinforcement yielding. So, it is impossible to investigate how much the

Table 3 Test results (unit :tonf · m)

Specimen	M_n calculated	Ultimte moment in test	Ratio	Specimen	M_n calculated	Ultimate moment in test	Ratio
CONTROL	1.93	1.92	1.00	SP3-CON	3.77	3.37	0.89
CF3-CON	2.84	2.75	0.97	SP3-LL	3.77	3.65	0.97
CF3-LL	2.84	2.46	0.87	SP3-HL	3.77	3.85	1.02
CF3-HL	2.84	2.92	1.03	SP6-CON	4.51	4.16	0.92
CF6-CON	3.72	3.83	1.03	SP6-LL	4.51	4.04	0.90
CF6-LL	3.72	3.61	0.97	SP6-HL	4.51	4.36	0.97
CF6-HL	3.72	3.21	0.86				

Table 4 Strain of re-bars and steel plate at ultimate loads (*:Yield)

Description	CONTROL	SP3-CON	SP3-LL	SP3-HL	SP6-CON	SP6-LL	SP6-HL
Re-bars	0.0019*	0.0005	0.0012	0.0023*	0.0011	0.0012	0.0011
Steel plate	-	0.0015*	0.0007	0.0011	0.0033*	0.0022*	0.0014*

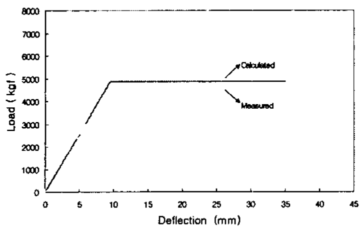
pre-loads affect the flexural strength of the beams. It seems that improvement of bonding between concrete and CFS contributed to the increse of ultimate moment capacity of pre-loaded beams. This can be regarded as installing line anchors between interface of pre-cracked concrete surface and CFS. From Fig. 4, the ultimate load of specimens with high residual stress is caused to coincide the yielding loads of steel plate and re-bars. In most specimens, the test results show lower moment capacities than nominal flexural strength by ACI Code provisions.

In order to investigate the effect of pre-load on measured deflection, a simple method using equivalent section properties by elastic modulus ratio is used. Fig. 5 shows the comparison of measured and calculated load-deflection relationships. With this equivalent section method, measured results are relatively close to those of calculated CONTROL and CF specimens as shown in Fig. 5. However, SP specimens show much different behavior because of premature bond failure between concrete and steel plate at post-yielding state of steel plate and pre-yielding state of reinforcement. That is to say, steel plate yields before re-bar yields like specimens without pre-load shown on Fig. 5 (c) and (e). As shown on Fig. 5 after yielding of steel plate, deformation of strengthened beams increases suddenly. Finally bond failure between concrete and strengthening materials is induced before yielding of reinforcement. The results of specimens at failure below the nominal strength.

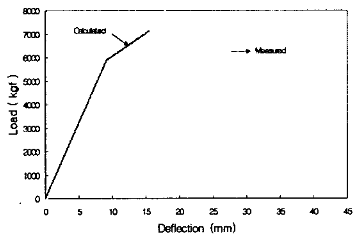
As shown on Fig. 2, all specimens, which have the same amount of reinforcement and strengthening materials, show similar slope. From Fig. 2, the pre-loading made no influence on the member stiffness after strengthening.

3.2 Failure Modes

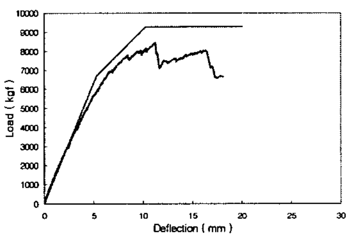
All specimens failed suddenly as bond failure between member and strengthening materials at ultimate loads.



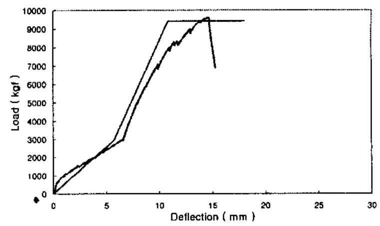
(a) CONTROL



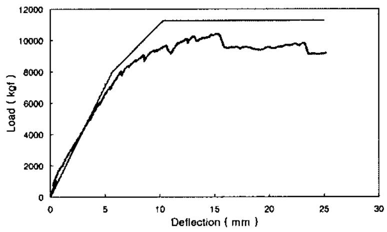
(b) CF3-CON



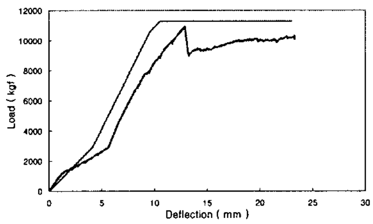
(c) SP3-CON



(d) SP3-HL



(e) SP6-CON



(f) SP6-HL

Fig. 5 Comparison of measured and calculated load-deflection relationship

Rip-off failure is appeared after reinforcement of specimens yield in the beams strengthened with carbon fiber sheet. However, in specimens with steel plate, bond failure between concrete and steel plate occurs before reinforcement yields. In any cases, the brittle failure caused by bond failure occurs.

From the crack propagation analysis, it can be known that crack length of strengthened members was short in comparison with control member as shown in Fig. 6. The reason can be analyzed that strengthening increases stiffness of the beam and improves resistance against loads.

However, at a certain level of load under evaluated failure load, strengthened materials. The main difference of structural behavior between the beams strengthened with CFS and steel plate is time of failure. Failure occurs after reinforcing bars are in post-yielding state for the beams strengthened with CFS as shown in Fig. 2. However, the failure in the beams with steel plate occurs before yielding of reinforcement. This failure is due to the bond failure of the interface between member and strengthening material before yielding of reinforcement or strengthening material. This failure also the following :

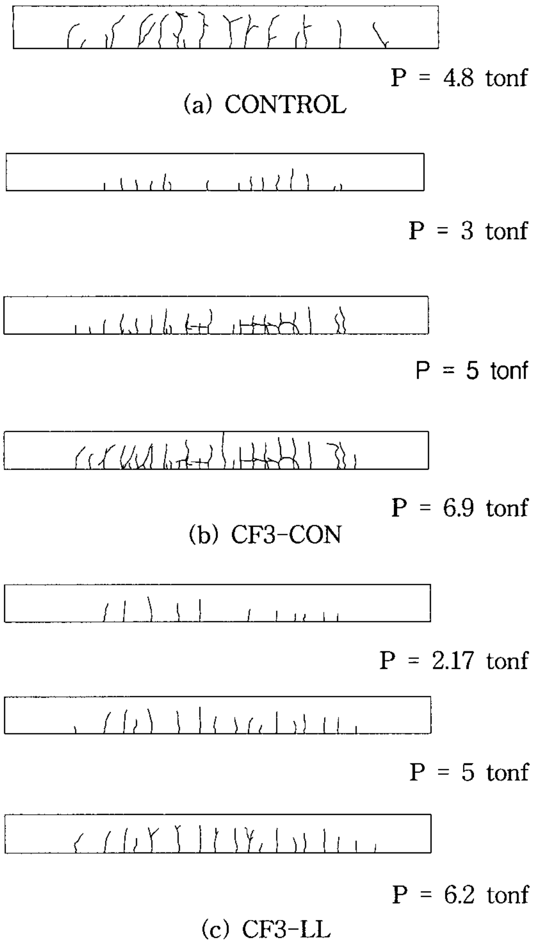


Fig. 6 Crack pattern

can be analyzed that yielding steel plate induce large strain. And this strain causes large shear stresses and result in shear failure at the interface of two materials.

4. Strength Estimation of Retrofitted Beams

To evaluate exact strength of retrofitted beams, the strain at the time of retrofitting works has to be considered. However, it is impossible to measure strains and stresses of flexural members of existing building to apply to the actual retrofitting design. In this study, the measured strains from test results are used to estimate strength as following.

Due to external influences such as premature failure, the ratios of maximum to strains at failure can be described by the composite factors K_p for the steel plate/ CFS and K_s for the reinforcement. From the previous research, K_p and K_s can be defined as below.[1,3,5,6,7]

$$\varepsilon_p = K_p \varepsilon_{pmax} \text{ with } K_p = 0.65 \sim 0.8$$

$$\varepsilon_s = K_s \varepsilon_{smax} \text{ with } K_S = 0.9 \sim 1.0$$

Fig 7. shows the forces for calculation of the ultimate moment M_R on a rectangular section. The following equilibrium conditions have to be met at the cross-section :

Table 5 Strength of specimens (unit :tonf.m)

Specimen	M_n calculated	M_R	Ultimate moment in test	Ratio	Specimen	M_n calculated	M_R	Ultimate moment in test	Ratio
CONTROL	1.93	1.93	1.92	1.00	SP3-CON	3.77	2.27	3.37	0.89
CF3-CON	2.84	3.24	2.75	0.97	SP3-LL	3.77	2.71	3.65	0.97
CF3-LL	2.84	2.55	2.46	0.87	SP3-HL	3.77	3.34	3.85	1.02
CF3-HL	2.84	3.05	2.92	1.03	SP6-CON	4.51	2.36	4.16	0.92
CF6-CON	3.72	4.34	3.83	1.03	SP6-LL	4.51	3.18	4.04	0.90
CF6-LL	3.72	3.87	3.61	0.97	SP6-HL	4.51	4.42	4.36	0.97
CF6-HL	3.72	3.84	3.21	0.86					

$\sum F = 0: T_p + T_s - C_c = 0$

$\sum M = 0: M_R - T_p(h - a/2) - T_s(d - a/2) = 0$

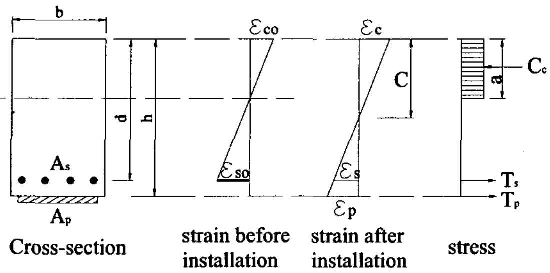


Fig. 7 Rectangular cross section

The· average strains during failure are given by
the following :

concrete : $\varepsilon_c = \dfrac{\varepsilon_p}{h-c} c + \varepsilon_{c0} \leq 0.003$

reinforcement :

$$\varepsilon_s = \frac{\varepsilon_p}{h-c}(d-c) + \varepsilon_{s0}$$

where $\varepsilon_s \leq \varepsilon_{smax} = K_s \varepsilon_y$

steel plate/CFS: $\varepsilon_{ptotal} = \varepsilon_{p0} + \varepsilon_p$

where $\varepsilon_{p0} + \varepsilon_{pmax} = \varepsilon_{pu}$

$$\varepsilon_p = K_p \varepsilon_{pmax} = K_p(\varepsilon_{pu} - \varepsilon_{p0})$$

The ε_{c0} and ε_{s0} allow for any strains present before the strengthening materials are installed. Any prestrain in the strengthening materials due to prestressing force is allowed at time t = 0 by ε_{p0}.

From the equilibrium condition, following equation can be derived.

$$M_R = A_p \varepsilon_p E_p (h - a/2) + A_s \varepsilon_s E_s (d - a/2) \quad (1)$$

where $\varepsilon_s = \dfrac{\varepsilon_p}{h-c}(d-c) + \varepsilon_{s0} \leq K_s \varepsilon_y$

$\varepsilon_p = K_p(\varepsilon_{pu} - \varepsilon_{p0})$

$a = \beta_1 c = (A_s \varepsilon_s E_s + A_p \varepsilon_p E_p)/0.85 f_{ck} b$

The Eq.(1) is used to estimate strength of specimens in Table 5, which shows more accurate strengths. From these results, the practical form of design formula is needed to be recommended as following Eq.(2)

$$M_R = A_p K_p \varepsilon_{pu} E_p (h - a/2) + A_s K_s \varepsilon_y E_s (d - a/2) \quad (2)$$

where $K_p = 0.65 \sim 0.8$, $K_S = 0.9 \sim 1.0$

However, more experimental researches are needed to determine the composite factor K_p, K_s for each load level at the time of rehabilitation.

5. Conclusions

The following conclusions are driven based on the test results:

(1) The failure of all specimens is brittle bond failure between the member and strengthening materials under pre-loading condition, even hough failure load levels are different.

(2) In the beams strengthened with CFS and maintained the bond after reinforcements yielded, resisting moments of the beams decreased as pre-loads increased. It indicates that design formulas has to include pre-loading effects.

(3) In the beams strengthened with steel plate that failed before reinforcement yielded, ultimate moments of the beams increased as pre-loads increased, because the steel plate yielded first before reinforcement yielded.

(4) Initial member stiffness after strengthening was not affected by pre-loading conditions. However, shifting points of load-deflection curves because of the reinforcement yielding were decreased by increasing pre-loads in CFS method.

(5) Crack length and deflections of strengthened members at the state of ultimate loads were decreased compared with those of control beams.

(6) Preset strains before strengthening materials have to be considered to estimate exact strength of retrofitted beams.

Acknowledgement

The authors gratefully acknowledge the financial support provided by Korea Science and Engineering Foundation. Thanks are also extended to Korea Sho-Bond Construction co. to fabricate strengthened specimens used in this research.

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