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Behavior of RC Beams Strengthened with Externally Post-Tensioning CFRP Strips

by K.-S. Choi, Y.-C. You, Y.-H. Park, J.-S. Park, and K.-H. Kim

Synopsis: Experimental study has been performed in order to investigate the behavior of RC beams strengthened with externally post-tensioning CFRP (Carbon Fiber Reinforced Polymer) strips. A total of 11 specimens have been manufactured of which specimens strengthened with bonded or unbonded CFRP strips considering the level of post-tensioning as experimental variable, and a specimen with simply bonded CFRP strips. The following phenomena have been observed through the experimental results. The specimen with simply bonded CFRP strips failed below 50% of its tensile strength due to premature debonding. On the other hand, all the specimens strengthened with post-tensioning CFRP strips showed sufficient strengthening performance up to the ultimate rupture load of the CFRP strips. Also, it was observed that the cracking loads and yield loads of the strengthened beams were increased proportionally to the post-tensioning level, but the ultimate loads were nearly equal regardless of the post-tensioning level and bonded or unbonded system. In addition, the yield loads and cracking loads of the beams with bonded post-tensioning systems were increased about 20% compared with those of the unbonded post-tensioning systems. However, the beams strengthened with unbonded post-tensioning CFRP strips showed ductile behaviour with large deflections resulting from the reduced member stiffness.

Keywords: bonded; CFRP strips; debonding failure; external post-tensioning; strengthening; unbonded

Ki-Sun Choi received his MS degree in architectural engineering from Hannam University, Korea. He is a researcher at the Building Research Department of the Korea Institute of Construction Technology.

Young-Chan You received his MS degree and Ph.D. in architectural engineering from Hanyang University, Korea. He is a chief researcher at the Building Research Department of the Korea Institute of Construction Technology.

Young-Hwan Park received his MS degree and Ph.D. in civil engineering from Seoul National University, Korea. He is a chief researcher at the Structure Research Department of the Korea Institute of Construction Technology.

Jong-Sup Park received his MS degree in civil engineering from Myongji University, Korea. He is a senior researcher at the Structure Research Department of the Korea Institute of Construction Technology.

Keung-Hwan Kim received his MS degree in structural engineering from Colorado State University and his PhD from University of Texas. He is vice-president of the Korea Institute of Construction Technology.

INTRODUCTION

Since CFRP (Carbon Fiber Reinforced Polymer) strips are manufactured by pultrusion process, their quality is superior to CFRP sheets and their construction process on job site can be shortened. CFRP strips factory manufactured are produced normally with smaller width and larger thickness than CFRP sheets because of the necessity to standardize their production. For this reason, bonding force between CFRP strips and concrete substrate is not sufficient to sustain tensile force in CFRP strips. Therefore premature debonding failure cannot be avoided when strengthening is done by simply bonding the CFRP strips (Seim, W., et al. 2001; Camata, G., et. al. 2003). The unused strength of CFRP strip caused by premature debonding can be fully utilized by post-tensioning CFRP strips at such a degree (El-Hacha, R., et. al. 2004; Zou, X. W. 2003).

There is much necessity to develop hardware and software technologies about strengthening with post-tensioning CFRP strips in order to activate its exploitation. Hardware technology includes basic elements such as development of high strength CFRP strips, anchorage system and jacking device. Software technology comprises the investigation on the behavior of strengthened beams with externally post-tensioning CFRP strips with respect to the specific parameters.

The researchers involved in this study have already developed high strength CFRP strips, anchorage system and jacking device (KICT, 2005). Using these basic technologies, the behavior of RC beams strengthened with externally post-tensioning CFRP strips has been investigated with respect to the level of post-tensioning, the bonded or unbonded post-tensioning systems.

EXPERIMENTAL PROGRAM

Post-tensioning systems

Strengthening with externally post-tensioning CFRP strips can be classified into bonded or unbonded systems. After introduction of post-tensioning, the bonded system permanently bonds the CFRP strips to the concrete member. On the other hand, the unbonded system just clamps the CFRP strips by means of mechanical anchorages after introduction of post-tensioning.

Level of post-tensioning

In bonded post-tensioning system, classical bending theory based on the perfect composite behavior can be applied if the level of post-tensioning is determined to prevent debonding until the CFRP strip reaches its ultimate rupture strength. However, the level of post-tensioning may be limited considering creep rupture of CFRP strips due to long-term loading and durability consideration against environmental condition. The failure mechanism of a beam strengthened with bonded CFRP strips with respect to the level of post-tensioning can be classified as illustrated in Fig. 1.

Zone 1: $\varepsilon_{fpi} > \varepsilon_{fu} - \varepsilon_{fd}$

Zone 1 corresponds to the case where the introduced post-tensioning exceeds the unused strain (rupture strain – debonding strain) of the CFRP strips after debonding. In such case, the ultimate load may be attained while maintaining composite behaviour without debonding of the CFRP strips.

Zone 2: $0 \le \varepsilon_{fpi} < \varepsilon_{fu} - \varepsilon_{fd}$

Zone 2 corresponds to the case where the introduced post-tensioning runs below the unused strain of the CFRP strips. Progressive debonding of the CFRP strip occurs as the load is increased. And, the bonded system switches into unbonded state after complete debonding and then reaches its ultimate load. In such case, bending theory based on strain compatibility conditions of the section cannot be applied since the CFRP strips and the member does not sustain complete composite behaviour at the end.

Zone 3: zero post-tensioning or simply bonded

Zone 3 corresponds to the case where post-tensioning is not introduced or the CFRP strip is simply clamped by means of a mechanical anchorage after bonding. The general behaviour of strengthened beams is similar to that of the beams with simply bonded CFRP strips. After the CFRP strip reaches its debonding strain, the system turns into unbonded state and then reaches the ultimate rupture load. The system with simply bonded CFRP strip is not expected to exhibit any strengthening performance in Zone 4.

Material properties

A design compressive strength of concrete of 18MPa has been planned considering the degradation state of the existing structure to be strengthened. D10 and D13 have been used for tension and compression rebars, respectively. D10 has also been selected for the shear rebar. The CFRP strips adopted in this study are the unidirectional CFRP strips developed by KICT in Korea. Table 1 and Table 2 summarize the material properties of the CFRP strips and epoxy resin.

Design of the specimens and test set-up

The specimens are small-scaled models manufactured with the shape and dimensions depicted in Fig. 2. Strengthening has been done by installing the CFRP strip in the tension zone at the soffit of the specimen with mechanical anchorage as shown in Fig. 3. Three-point load has been applied.

The specimens consist of both bonded and unbonded systems with specific levels of post-tensioning. The levels of post-tensioning were selected with reference to the tensile strength of the CFRP strips, that is 0%, 20%, 40% and 60%. The bonded system has been manufactured by bonding the CFRP strip with the specimen by means of epoxy resin after the introduction of post-tensioning. A control specimen and a specimen with simply bonded CFRP strip have also been manufactured to compare the structural performances of each post-tensioning system. Table 3 lists the parameters of each specimen.

RESULTS

Failure mode

As shown in Fig. 4, the specimen strengthened with simply bonded CFRP strip failed by the abrupt debonding of CFRP strips starting from the center to the extremity. The strain of the CFRP strip measured at debonding failure reached 6,852μ, which corresponds to nearly 50% of its tensile strength.

All the specimens strengthened with bonded CFRP strips which are post-tensioned below 60% of their tensile strength turned into unbonded states after debonding. Final failure modes were governed by CFRP rupture at the mid-span (Fig. 5(a)). However, the specimen post-tensioned with 70% of the tensile strength reached the ultimate state by the rupture of CFRP strips without any occurrence of debonding (Fig. 5(b)).

From the experimental results, it was observed that the failure mode of the beam strengthened with bonded system was affected by the level of post-tensioning that has been introduced in the CFRP strips. On the contrary, all the specimens strengthened with unbonded system failed by the rupture of the CFRP strip regardless of the level of post-tensioning as shown in Fig. 6.

Effects of strengthening

Table 4 summarizes the experimental results. As mentioned above, the specimen strengthened with simply bonded CFRP strip showed debonding failure at 50% of the tensile strength of the CFRP strip without developing sufficient strengthening. On the other hand, the anchorage system used in this study was able to clamp the CFRP strips up to their rupture strength. Therefore, it was verified that all the specimens strengthened with post-tensioning CFRP strips using the anchorage system reached the rupture strength of the CFRP strip prior to concrete crushing. The ultimate loads were nearly equal regardless of the level of post-tensioning.

Fig. 7 shows the losses of the CFRP strain for some length of time. As shown in Fig 7, it is clear that the post-tensioned CFRP strain rapidly decreases with anchorage set, but the decreasing rate is reduced and converged to a certain value. In this post-tensioning system, total losses of post-tensioned CFRP strain for 300 hours are about 5% of its initial strain.

Load-deflection curve

Fig. 8 and 9 show the load-deflection relation of the specimens with bonded and unbonded systems with respect to the level of post-tensioning. Observation of the curves reveals that the cracking load, yield load and debonding load increase with the level of post-tensioning, but the deformation capacity after debonding decreases.

The general load-deflection curves of specimen strengthened with post-tensioning level below 60% of the CFRP strength are characterized by the transient diminution of the load caused by the sequential first and second debonding from mid-span to beam end. These diminutions imply that bonded system is switched into unbonded system. After this, deflection is increased rapidly up to the ultimate load.

The specimen strengthened with post-tensioning level of 70% of the CFRP strength maintained consistent stiffness as a composite section since debonding did not occur. As a result, the deflection and crack width were reduced and the maximum loads were increased.

On the other hand, the stiffness of the specimens strengthened with unbonded system become lower because of the non-composite action between members and CFRP strips. The large deflection caused by reduced member stiffness resulted in ductile behavior up to failure state.

Stiffness of the beam

Fig. 10 compares the load-deflection curves of the beam with bonded or unbonded CFRP strips. The initial stiffness 'A' effective for the whole section and stiffness 'B' of the cracked section do not show any significant dependence on either bonding or unbonding status of the CFRP strip. After yielding of the steel rebar, the beams with bonded system maintained stiffness 'C' until debonding as a composite section with increased load carrying capacity, but the beam with unbonded system maintained stiffness 'D' as a non-composite section from the beginning. The beam with bonded system being switched into non-composite section after debonding, its stiffness degrades to become stiffness 'D'.

Longitudinal strain gradient of CFRP strips

Strain gauges were installed at spacing of 150 mm all along the length in order to survey the longitudinal strain gradient of CFRP strip. Measurement results are plotted in Fig. 11 and 12.

In a beam with bonded system, the strain measured in CFRP strip exhibited linear distribution along the length at first, the strain gradient was increased proportionally to the load sharing rate of the CFRP strip after the yield of steel rebar. After debonding of the CFRP strips, the slope of the strain distribution was drastically reduced as the section switched into a non-composite section. However, the strain distributions of the CFRP strip in the unbonded zone were different due to local friction force between CFRP strips and concrete.

In a beam with unbonded system, the strain of the CFRP strip exhibited identical distribution all over the loading zone. Since the stress is redistributed along the length of the CFRP strip, smaller strain is measured at identical measuring points compared with bonded system. Moreover, the strain of the CFRP strip at ultimate state appeared to be decreased by about 10% compared with bonded system. Table 5 shows the ultimate strains of the CFRP strip in bonded or unbonded systems

CONCLUSIONS

Tests have been performed in order to investigate the flexural behaviour of RC beams strengthened with externally post-tensioning CFRP strips with respect to the level of post-tensioning and the bonding or unbonding of CFRP strip. The following conclusions are drawn from the test results.

1) The specimen strengthened with simply bonded CFRP strip failed by debonding at about 50% of the tensile strength of CFRP strip.

2) In the case of the specimens strengthened with bonded CFRP strip post-tensioned below 60% of its tensile strength, final failure was governed by the rupture of CFRP strip after being switched into unbonded state with debonding of CFRP strips.

3) Strengthening with bonded CFRP strip post-tensioned exceeding 70% of its tensile strength can lead to rupture of CFRP strip without debonding.

4) The cracking and yield loads of the strengthened beams were increased proportionally to the level of post-tensioning, but the ultimate loads were nearly identical regardless of the post-tensioning level and bonded or unbonded system.

5) The beams strengthened with unbonded CFRP strips showed ductile behavior with large deflections resulting from the reduced member stiffness.

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Table 1— Mechanical properties of CFRP strip

Thickness (mm)	Width (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain (%)
1.5	50	2,167	173	1.25

Table 2— Mechanical properties of epoxy resin

Tensile strength (MPa)	Tensile shear strength (MPa)	Pot life (min)
33.5	4.3	26

Table 3— Summary of the test beams

Specimen	Strengthening Details	Strengthening system	Post-tensioning, f_{fpi}/f_{fu} *(%)
Control	-	-	-
NB1	CFRP Width : 50mm CFRP THK : 1.5mm Bond length : 1,900mm	Simply bonded	-
PB1-0R		Bonded post-tensioning system	0
PB1-2R			20
PB1-4R			40
PB1-6R			60
PB1-7R			70
PU1-0R		Unbonded post-tensioning system	0
PU1-2R			20
PU1-4R			40
PU1-6R			60

* f_{fpi} : Post-tensioning stress, f_{fu} : Ultimate tensile strength of CFRP strip

Table 4— Test results

Beam	P_{cr} (kN)	P_y (kN)	P_d (kN)	P_{max} (kN)	ε_{fpi} (μ)	ε_{fd} (μ)	ε_f (μ)	ε_{fu} (μ)	Failure mode*
Control	18.2	40.4	-	-	-	-	-	-	A
NB1	13.7	56.3	77.0	77.0	-	6,852	6,852	6,852	B
PB1-0R	24.5	55.4	80.5	121.5	0	7,002	12,218	12,218	C
PB1-2R	26.4	71.6	105.0	123.0	2,367	8,309	10,317	12,684	C
PB1-4R	42.4	85.2	120.1	125.2	5,011	6,882	7,239	12,250	C
PB1-6R	51.8	100.5	119.6	122.8	7,410	6,023	6,098	13,508	C
PB1-7R	61.9	115.5	-	126.5	8,069	-	4,987	13,056	D
PU1-0R	18.9	43.0	-	115.0	0	-	10,655	10,655	D
PU1-2R	33.5	56.4	-	119.8	2,540	-	8,662	11,202	D
PU1-4R	47.0	75.9	-	120.7	5,200	-	6,257	11,457	D
PU1-6R	54.1	83.6	-	122.5	7,402	-	4,469	11,871	D

* A: concrete crushing after steel yield,
B: debonding failure of CFRP strip after steel yield,
C: rupture of CFRP strip after debonding of CFRP strip,
D: rupture of CFRP strip after steel yield.

$P_{\_}$
- cr : crack load
- y : steel yield load
- d : CFRP debonding load
- max : maximum load

$\varepsilon_{\_}$
- fpi : CFRP initial post-tensioning strain
- fd : CFRP debonding strain
- f : CFRP measured strain
- fu : CFRP total ultimate strain ($\varepsilon_{fpi}+\varepsilon_f$)

Table 5— Comparison of CFRP ultimate strains in bonded or unbonded post-tensioning systems

Post-tensioning	Bonded system-		Unbonded system-		ε_{fu} /ε_{fu}
	ε_{fu} (μ)	ε_{fu} /ε_{fu}	ε_{fu} (μ)	ε_{fu} /ε_{fu}	
Simple bond	6,852	0.55	-	-	-
0%	12,218	0.98	10,655	0.85	0.87
20%	12,684	1.01	11,202	0.89	0.88
40%	12,250	0.98	11,457	0.91	0.94
60%	13,508	1.08	11,871	0.95	0.88
70%	13,056	1.04	-	-	-

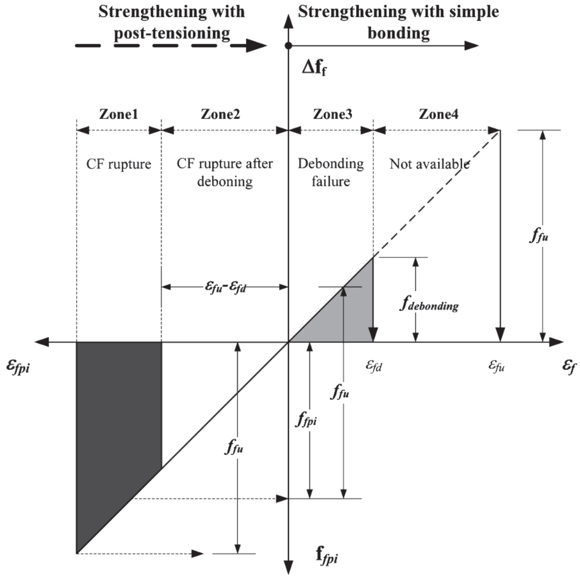


Figure 1— Failure mechanism of beams strengthened with bonded CFRP strips with respect to the level of post-tensioning

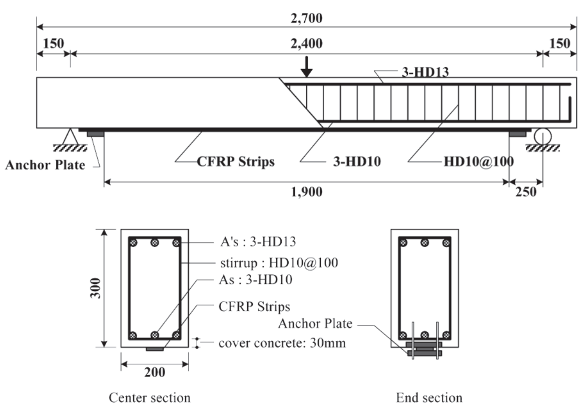
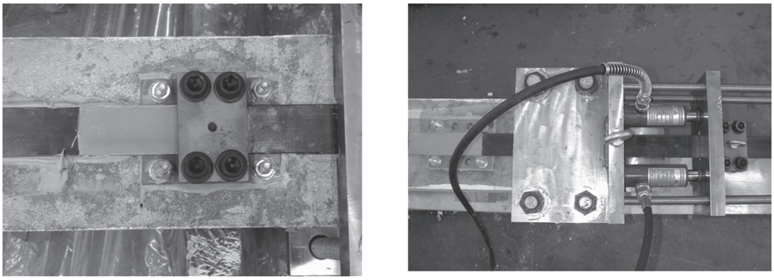


Figure 2— Dimensions and details of test beam



(a) Anchorage system (b) Jacking device

Figure 3—Anchorage and jacking device for post-tensioning CFRP strips

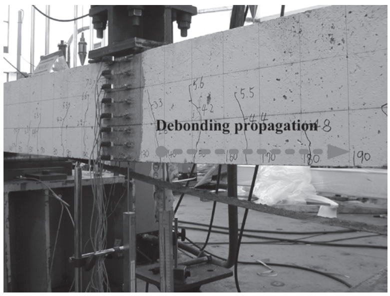
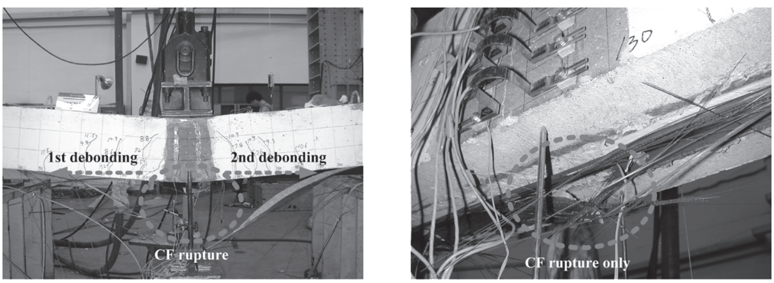


Figure 4—Typical failure mode of beam with simply bonded CFRP strips



(a) below 60% of tensile strength (b) more than 70% of tensile strength

Figure 5—Typical failure mode of beams strengthened with bonded post-tensioning CFRP strips

Figure 6—Typical failure mode of beam with unbonded post-tensioning CFRP strips

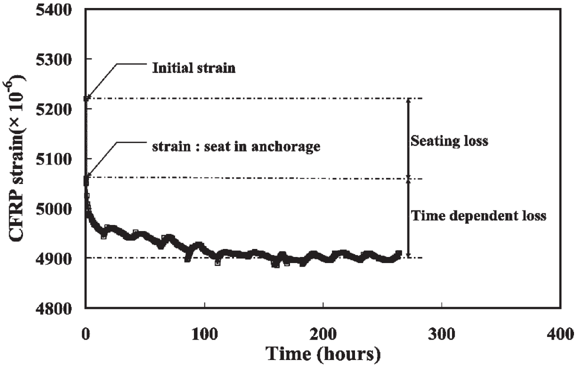


Figure 7—Losses of post-tensioned CFRP strain

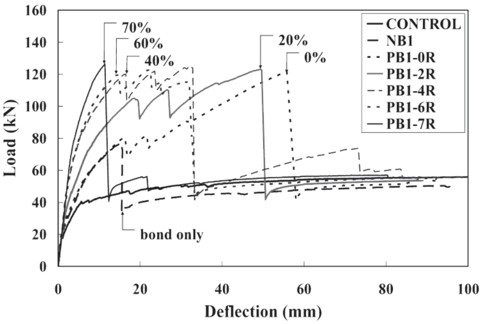


Figure 8—Load-deflection curves of beams strengthened with bonded post-tensioning systems

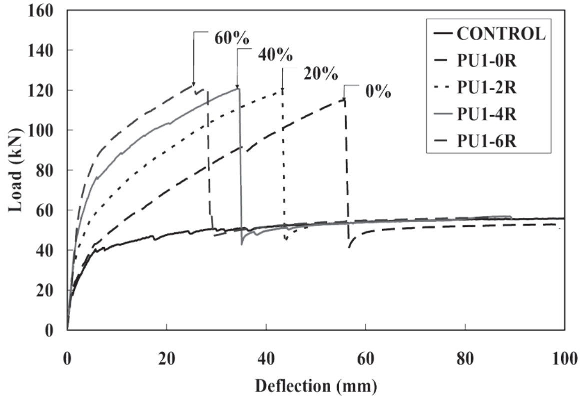


Figure 9—Load-deflection curve of beams strengthened with unbonded post-tensioning systems

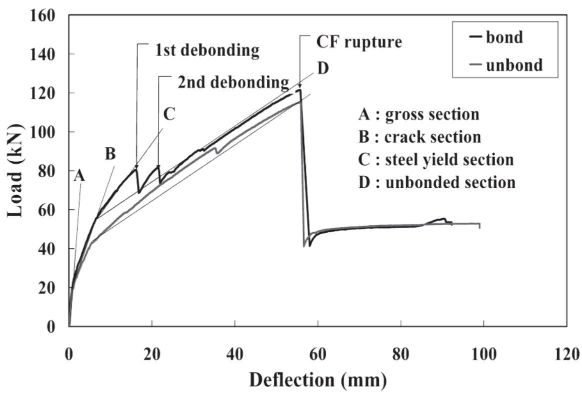


Figure 10—Typical load-deflection curves of beams with bonded or unbonded post-tensioning systems

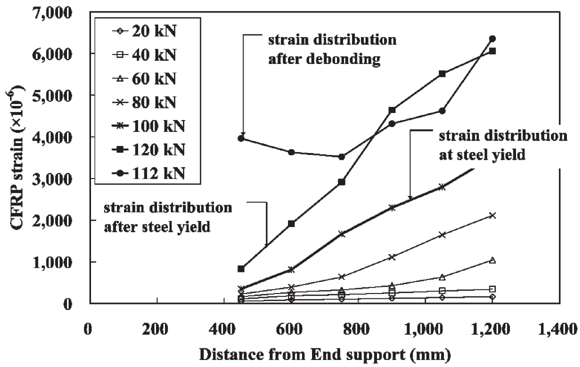


Figure 11—Typical strain distribution of the bonded CFRP strips along the length

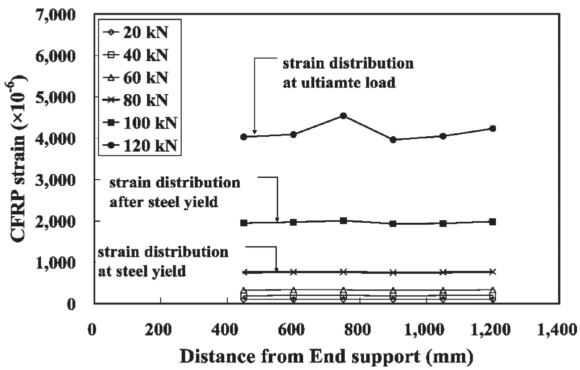


Figure 12—Typical strain distribution of the unbonded CFRP strips along the length