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Composite Strips with Various Anchor Systems for Retrofitting Concrete Beams

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Abstract: This paper presents the performance of anchor systems for reinforced concrete beams retrofitted with carbon fiber reinforced polymer (CFRP) strips. Nine simply-supported beams are tested with various anchor systems such as steel hooks, steel plates with anchor bolts, CFRP anchor plates, and near-surface mounted (NSM) CFRP strip. The effects of these anchors on the behavior of the retrofitted beams are discussed, including load-carrying capacity, failure modes, and ductility characteristics. Test results indicate that end-anchorage is an important parameter when a CFRP-retrofit design is conducted. Mechanical bolts and NSM CRFP anchors are recommended.

Keywords: anchor, beam, carbon fiber reinforced polymer, concrete, retrofitting.

1. Introduction

Structural rehabilitation is one of the most critical issues in the civil engineering community. For example, over 25% of bridges in the United States are structurally deficient or functionally obsolete, and $188 billion will be required to eliminate such bridges.[1] Typical sources of deterioration include use of deicing salts on highway bridges, increased service loads, ageing, chemical damage including corrosion, and impact of heavy trucks.[2-4] Carbon fiber reinforced polymer (CFRP) composites may be used for retrofitting reinforced concrete members. The advantages of CFRP-retrofit are favorable strength-to-weight ratios, non-corrosive performance, good fatigue and chemical resistance, prompt site application, and reduced long-term maintenance expenses.[5,6] Recent site demonstration projects support the efficacy of such a rehabilitation method to improve the performance of constructed concrete members.[7-10] Although CFRP-retrofit methods provide noticeable improvement to the behavior of reinforced concrete structures (e.g., load-carrying capacity), the performance of retrofitted members is significantly influenced by the integrity of a retrofit system: premature debonding failure of CFRP composites results in the failure of a retrofit system. Attention should therefore be paid to the behavior of anchorage that affects the performance of CFRP-retrofitted members. Khalifa et al.[11] examined the behavior of anchorage for near-surface-mounted FRP reinforcing bars, namely, epoxy-filled groove anchorage. U-wrap anchors were also studied for the application of FRP sheets. The anchors precluded the failure of FRP reinforcing systems. Lamanna et al.[12] conducted an experimental program to evaluate the performance of reinforced concrete beams retrofitted with CFRP strips. Mechanical bolting (spike anchors) was carried out to anchor the strips along the tensile soffit of the beams. Such an anchoring method reduced FRP-installation time and resulted in improved ductility when compared to those of conventional chemical bond applications. Pimanmas and Pornpongsaroj[13] tested reinforced concrete beams retrofitted with CFRP plates, including various types of FRP U-wrap anchors. The failure of retrofitted beams was affected by the configuration of anchorage (i.e., bond angles and number of FRP layers). Kim et al.[14,15] studied anchor systems for reinforced concrete beams retrofitted with prestressed CFRP sheets. Test parameters included the size of anchorage and prestressed U-wrap anchors. Time-dependent behavior of the anchor system was examined. Crack propagation along the CFRP-concrete interface (when the retrofitted beams were loaded) was influenced by the type of anchors. A closed-form solution was developed to predict the behavior of the proposed anchor systems.

As described above, end-anchorage plays an important role in the behavior of reinforced concrete beams retrofitted with CFRP composites. The primary focus of extant research programs has been on the use of U-wrap anchors. There is a need for research to develop other types of anchor systems. In this paper, an experimental program is conducted to examine the performance of various anchor systems for CFRP strips bonded to the tensile soffit of reinforced concrete beams.

2. Research significance

End-anchorage is one of the most important considerations when retrofitting reinforced concrete beams using CFRP strips.

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Failure characteristics and load-carrying capacity of CFRP-retrofitted beams are significantly influenced by the performance of anchor systems. Although previous research discusses use of a variety of anchor systems for such a retrofit method, there is still a dearth of understanding of the performance of mechanical anchors. This paper experimentally addresses the efficacy of various anchoring methods, including their performance and failure mode.

3. Experimental program

An experimental program was conducted using seven anchor systems for reinforced concrete beams retrofitted with CFRP strips and two counterpart control beams. The following summarizes beam details, test set-up, and instrumentation.

3.1 Materials

The concrete mixed in the laboratory had a 28-day compression strength of 26 MPa with an elastic modulus of 33 GPa, on average. Table 1 shows the mix design used for this study. The steel reinforcing bar showed 350 MPa and 483 MPa for yield and ultimate strengths, respectively, with an elastic modulus of 206 GPa. The CFRP composite strips had a tensile strength of 2,664 MPa with a modulus of 188 GPa and a rupture strain of 1.42%. The bonding agent used was an epoxy adhesive, including compression and tension strengths of 79 MPa and 37 MPa, respectively.

3.2 Beam details

The reinforced concrete beams used for this research had dimensions of 200 mm wide × 200 mm deep × 1,900 mm long

Table 1 Mix design of concrete beams.

Water (kg/m^3)	177
Ordinary Portland cement (3.16 g/cm^3) (kg/m^3)	362
Fine aggregate (sea sand; 2.62 g/cm^3) (kg/m^3)	709
Coarse aggregate (Andesite crushed rock; 2.73 g/cm^3) (kg/m^3)	1,071
Air-entraining and water-reducing agent (1.0 g/cm^3) (kg/m^3)	0.9

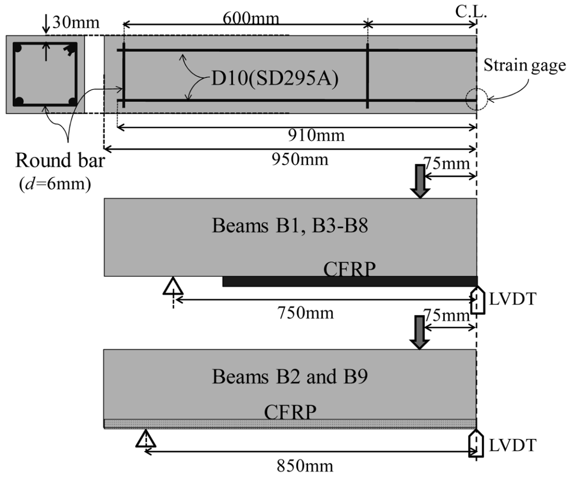


Fig. 1 Details of beam specimens.

and were reinforced with D10 bars (A_s = 71 mm^2 each), as shown in Fig. 1. A reinforcement ratio of 0.4% was used to ensure the flexural failure of the beams: shear behavior was not an issue, taking into account the low reinforcement ratio. Table 2 summarizes the details of the test beams. A single layer of CFRP strip (50 mm wide × 1.2 mm thick) and anchorage were adhesively bonded to the beams. The anchor system studied here included: steel hooks (*H*), mechanical anchor bolts (*A*), steel plates (*P*), CFRP plates (*C*) in rectangular (R) or trapezoidal (*T*) shapes, and near-surface mounted (*NSM*) CFRP strip, as shown in Fig. 2. The CFRP strips and anchorage were adhesively bonded to the beams. The steel hook and plates made of mild steel were 50 mm wide × 1.2 mm thick × 210 mm long (B4) and 170 mm wide × 6 mm thick × 50 mm long (B6), respectively. The CFRP plate had dimensions of 200 mm wide × 1.2 mm thick × 210 mm long and 50 mm wide × 1.2 mm thick × 100 mm long for the trapezoidal (B7) and the rectangular (B8) shapes, respectively. Two support pads were placed for Beam 8 (Fig. 2b) to permit the bond-slip of the longitudinal CFRP strip. The steel hooks and anchor bolts were installed after drilling the concrete with an embedment depth of 25 mm. The anchor bolts were 10 mm in diameter with a length of 60 mm

Table 2 Details of test beams with various anchor systems.

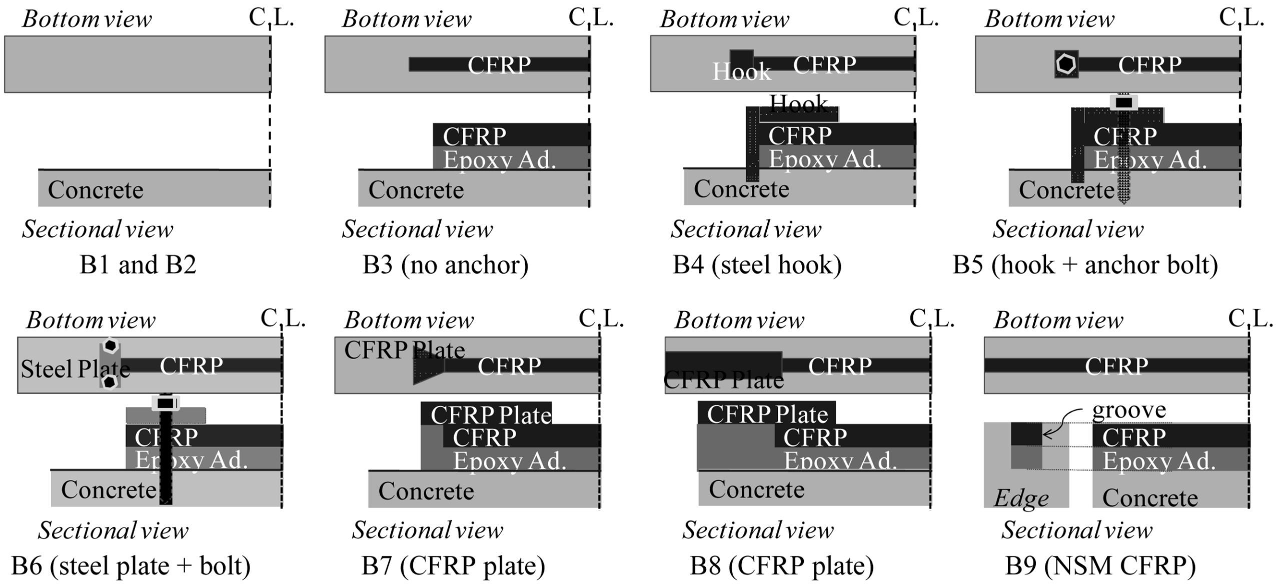
Beam	CFRP	Anchorage[a]	Bending moment (kNm)		Rebar strain (10^{-6})		CFRP strain (10^{-6})		Failure mode[c]
			Yld	Ult	Yld	Ult	Yld	Ult	
B1	None	None	8.3	15.0	1,779	31344	-	-	Crushing
B2	None	None	7.6	12.1	1,767	N/A[b]	-	-	Crushing
B3	Yes	No	11.6	15.1	1,949	N/A[b]	2,049	3,480	End-peel
B4	Yes	H	11.6	15.6	1,625	16,975	1,791	2,780	End-peel
B5	Yes	HA	11.6	14.5	1,902	25,927	N/A[d]	N/A[d]	IC
B6	Yes	PA	14.9	18.5	1,837	13,307	2,580	4,145	IC
B7	Yes	CT	11.6	14.9	1,525	11,327	1,777	3,020	End-peel
B8	Yes	CR	11.6	14.8	1,658	10,959	1,822	2,650	End-peel
B9	Yes	NSM	13.3	21.1	1,759	N/A[b]	2,087	6,215	Crushing

Yld = at yielding; Ult = at ultimate

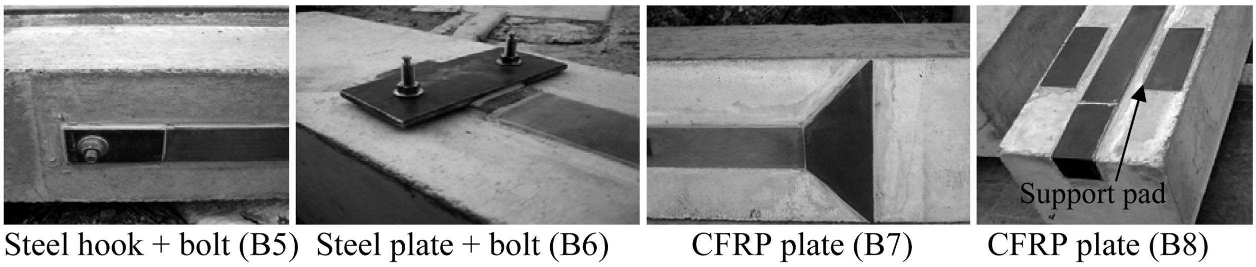
a : H = steel hook; A = anchor bolt; P = steel plate; CT = trapezoidal CFRP anchor; CR = rectangular CFRP anchor; NSM = near-surface mounted CFRP strip

b : malfunctioning of strain gage

c : crushing = concrete crushing; End-peel = end-peeling of CFRP strip; IC = intermediate-crack-induced debonding



(a) Schematic view



(b) Selected photographs

Fig. 2 Various anchor systems.

(B5 and B6). A groove size of 50 mm wide × 5 mm deep was used for the NSM CFRP strip (B9). A buffering material was placed in between Beam B9 and its supports for the slip of the CFRP. The span length of Beam B9 was 200 mm longer than other retrofitted beams (Fig. 1) to permit more deflection of the beam having the NSM anchorage. Such an experimental scheme is justified by the fact that the NSM CFRP system could exhibit better bond performance when compared to externally bonded CFRP composites[16] and thus a larger span length was expected to result in significant bending of the beam.

3.3 Test set-up and instrumentation

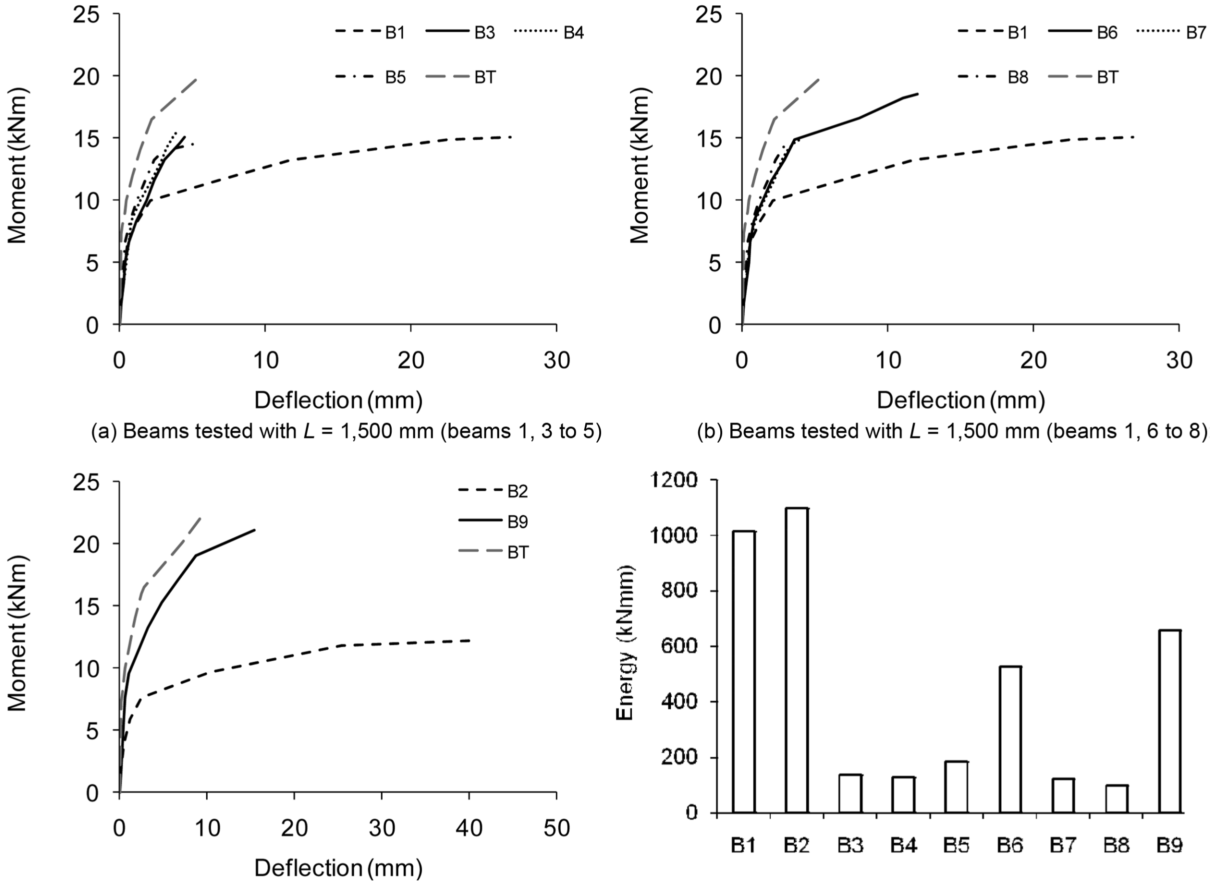
The beams were monotonically loaded in four-point bending until failure occurred, as shown in Fig. 1. One linear variable displacement transducer (LVDT) was positioned at midspan of each beam to measure vertical deflection. Strain gages were bonded to the CFRP and steel bar at midspan. All beams were tested with a load-control mode at a loading rate of 2 kN/min.

4. Results and discussions

4.1 Flexural behavior

Table 2 summarizes the test results of the beam specimens. The retrofitted beam without any anchorage (B3) showed an increase of 39.8% in yield moment when compared to the unretrofitted control beam (B1); however, the ultimate moments of these two beams were almost the same (15 kNm) because of the premature debonding failure of the CFRP. The beams with the steel hooks (B4) and anchor bolts (B5) exhibited very similar responses to the beam without any anchorage (B3), as shown in Table 2. The beam with the steel plates and anchor bolts (B6) showed an increase of 79.5% in yield moment compared to the control (B1), whereas the ultimate moment was improved by 23.3%. The beams with the CFRP plate anchors (B7 and B8) showed a very similar moment-carrying capacity each other; however, the CFRP strain of Beam B7 at ultimate was 14.0% greater than that of Beam B8 at failure (Table 2). This observation indicates that the trapezoidal anchor plates were more effective than the rectangular plates in terms of anchoring the CFRP. The beam retrofitted with the NSM CFRP strip (B9) showed an increase of 75.0% and 74.4% in the yield and ultimate capacities, respectively, when compared to the unretrofitted control beam (B2). The usable strains of the CFRP strips varied from 18.7% to 43.8% of the rupture strain of the CFRP ($\varepsilon_{u\text{-}CFRP}$ = 0.0142) when the retrofitted beams failed (Table 2).

Figure 3 shows the moment-deflection response of the test beams. A simple analytical model was compared with the experimental cases for a reference purpose. The predictive model was developed based on displacement compatibility and force equilibrium with the following assumptions: plane section remains plane after bending of the beam and perfect bond exists between the CFRP and concrete beam. All retrofitted beams exhibited abrupt failure due to either debonding of the CFRP or crushing of the



(a) Beams tested with L = 1,500 mm (beams 1, 3 to 5)
(b) Beams tested with L = 1,500 mm (beams 1, 6 to 8)
(c) Beams tested with L = 1,700 mm (beams 2 and 9)
(d) Energy dissipation capacity of each beam

Fig. 3 Flexural response of test beams (note: 'BT'= predictive model for retrofitted beam).

concrete. The beam with the NSM CFRP strip (B9) showed the largest deflection (15.4 mm) and highest moment-carrying capacity (21.1 kNm) among the retrofitted beams. Figure 3(d) compares the energy dissipated by the beams until failure occurred. The energy was calculated by numerically integrating the area under the load-deflection curve of each beam. The energy capacity of the test beams was significantly influenced by the type of anchors. The unretrofitted control beams (B1 and B2) showed an energy of over 1,000 kNmm, whereas the retrofitted beams exhibited lower energies. Such an observation is attributed to the very ductile behavior of the control beams, as shown in Fig. 3(a) through (c). The beam retrofitted with the NSM CFRP strip (B9) showed the highest energy dissipation capacity (i.e., 59.7% of the unretrofitted B2 beam) and the beam with the mechanical anchorage (steel plates with anchor bolts, B6) followed. All other beams demonstrated energy dissipation capacities as low as 9.6% when compared to the unretrofitted beam (B1).

4.2 Failure mode

The failure mode of the beams is shown in Fig. 4. The beam with the steel hooks (B4) showed end-peeling of the CFRP (Fig. 4(a)). This observation illustrates that the embedment depth of the hook anchorage in the concrete (25 mm) might not be sufficient to preclude such a premature debonding failure. The beam with the hooks and anchor bolts (B5) failed by intermediate-crack-induced debonding (*IC-debonding* hereafter), as shown in Fig. 4(b). The IC-debonding occurred near midspan of Beam B6 (steel plates with anchor bolt) and propagated towards the termination points of the strip. End-peeling failure, however, was not observed for Beam B6 because of the mechanical anchor system (Fig. 4(c)). The beam retrofitted with the NSM CFRP strip did not show any noticeable debonding of the CFRP (Fig. 4(d)), whereas the concrete in compression crushed at a moment of 21.1 kNm.

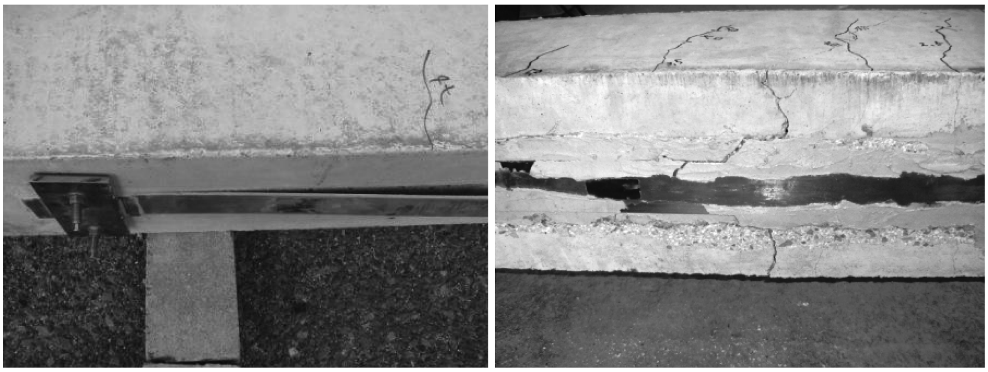
4.3 Ductility

Figure 5 shows the ductility characteristics of the retrofitted beams. A ductility index was defined to quantify the flexure of the beams:

$$DI = \frac{E_{ult}}{E_{yld}} \tag{1}$$

where DI is the ductility index and E_{ult} and E_{yld} are the energies dissipated until the ultimate and yield loads are achieved, respectively. Such an index provides crucial information to understanding the efficacy of the anchor systems studied here, given that CFRP composites do not exhibit a yield plateau unlike conventional construction materials such as steel and thus the retrofitted beams show brittle failure as explained above. The ductility indices of Beams 1 and 2 (unretrofitted) were 46.8 and 31.6, respectively. The specimen without any anchors (Beam B3) showed a ductility index of 2.5, while some specimens with anchorage (Beams B4, B7, and B8) exhibited similar indices (Fig. 5). The specimens with the anchor bolts (Beams B5 and 6) showed ductil-

(a) End-peel debonding failure (Beam B4) (b) Intermediate-crack-induced debonding (Beam B5)



(c) Intermediate-crack-induced debonding (Beam B6) (d) NSM CFRP strip (Beam B9)

Fig. 4 Failure mode of test beams.

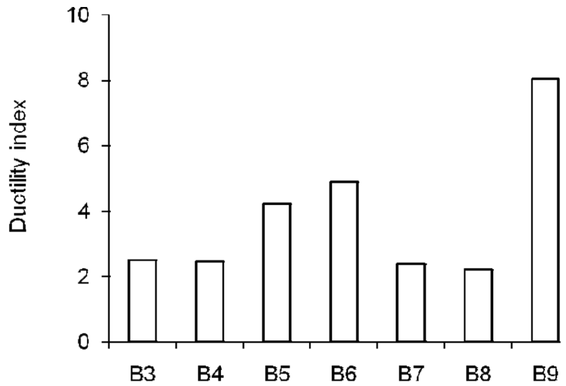


Fig. 5 Ductility index of retrofitted beams.

ity indices of 4.2 and 4.9, respectively. These observations indicate that mechanical anchor bolts can significantly enhance the ductility of CFRP-retrofitted beams. The specimen with the NSM CFRP strips showed the highest ductility index of 8.0. This is attributed to the improved bond between the CFRP and concrete.

5. Summary and conclusions

This paper has addressed the performance of anchor systems for reinforced concrete beams retrofitted with CFRP strips. A total of nine beams were tested with various types of anchors, including steel hooks, mechanical anchor bolts, steel and CFRP plates, and NSM anchorage. The following is concluded.

1) The beams retrofitted with the CFRP strip showed an average increase of 60.7% in yield moment when compared to their counterpart unretrofitted beams. The ultimate moment-carrying capacity of the unretrofitted beams varied depending upon the type of anchorage. The trapezoidal anchor plates were more effective than the rectangular plates. The performance of the hook anchors was not satisfactory: premature CFRP-debonding occurred. The beam with the NSM CFRP strip showed the best performance in terms of moment-carrying capacity among the test beams.

2) End-peeling failure was observed for the specimens with the hook anchors, while IC-debonding was noticed for the beams with the mechanical bolts and steel plates. No premature debonding of the NSM CFRP strip was observed. The failure of the NSM beam was governed by concrete crushing.

3) Structural ductility of the retrofitted beams was significantly, lower than that of the unretrofitted control beams primarily due to the failure of the anchor system. The mechanical bolt anchors were an effective means to improve the ductility of the retrofitted beams. The beam with the NSM anchorage showed noticeable improvement in ductility because of the enhanced bond between the CFRP and concrete.

References

1. ASCE, Report Card for America's Infrastructure, American Society of Civil Engineers, Reston, VA, USA, 2005.

2. Kim, Y. J. and Heffernan, P. J., "Fatigue Behavior of Structures Strengthened with Fiber Reinforced Polymers: State-of-the-Art," *Journal of Composites for Construction*, Vol. 12, No. 3, 2008, pp. 246~256.

3. Kim, Y. J. and Yoon, D. K., "Identifying Critical Sources of Bridge Deterioration in Cold Regions through the Con-

structed Bridges in North Dakota," *Journal of Bridge Engineering*, Vol. 15, No. 5, 2010, pp. 542~552.

4. Yoshitake, I., Kim, Y. J., Yumikura, K., and Hamada, S., "Moving-Wheel Fatigue for Bridge Decks Strengthened with CFRP Strips Subject to Negative Bending," *Journal of Composites for Construction*, Vol. 14, No. 6, 2010, pp. 784~790.

5. Bakis, C. E., Bank, L. C., Brown, V. L., Cosenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S. H., and Triantafillou, T. C., "Fiber-Reinforced Polymer Composites for Construction-State-of-the-Art Review," *Journal of Composites for Construction*, Vol. 6, No. 2, 2002, pp. 73~87.

6. Teng, J. G, Chen, J. F., Smith, S. T., and Lam, L., "Behavior and Strength of FRP-Strengthened RC Structures: a State-of-the-Art Review," *Structures and Buildings*, Vol. 156, No. 1, 2003, pp. 51~62.

7. Karbhari, V. and Seible, F., "Fiber Reinforced Composites-Advanced Materials for the Renewal of Civil Infrastructure," *Applied Composite Materials*, Vol. 7, 2000, pp. 95~124.

8. Kim, Y. J., Green, M. F., Fallis, G. J., Wight, R. G., and Eden, R., "Damaged Bridge Girder Strengthening: Field Application of Prestressed Fiber-Reinforced Polymer Sheets," *Concrete International, American Concrete Institute*, Vol. 28, No. 11, 2006, pp. 47~52.

9. Kim, Y. J., Green, M. F., and Fallis, G. J., "Repair of Bridge Girder Damaged by Impact Loads with Prestressed CFRP Sheets," *Journal of Bridge Engineering*, Vol. 13, No. 1, 2008, pp. 15~23.

10. Taljsten, B., Hejll, A., and James G., "Carbon Fiber-Reinforced Polymer Strengthening and Monitoring of the Grondals Bridge in Sweden," *Journal of Composites for Construction*, Vol. 11, No. 2, 2007, pp. 227~235.

11. Khalifa, A., Alkhrdaji, T., Nanni, A., and Lansburg, S., "Anchorage of Surface Mounted FRP Reinforcement," *Concrete International*, Vol. 21, No. 10, 1999, pp. 49~54.

12. Lamanna, A. J., Bank, L. C., Scott, D. W., "Flexural Strengthening of Reinforced Concrete Beams by Mechanically Attaching Fiber-Reinforced Polymer Strips," *Journal of Composites for Construction*, Vol. 8, No. 3, 2004, pp. 203~210.

13. Pimanmas, A. and Pornpongsaroj, P., "Peeling Behaviour of Reinforced Concrete Beams Strengthened with CFRP Plates under Various End Restraint Conditions," *Magazine of Concrete Research*, Vol. 56, No. 2, 2004, pp. 73~81.

14. Kim, Y. J., Wight, R. G., and Green, M. F., "Flexural Strengthening of RC Beams with Prestressed CFRP Sheets: Development of Non-Metallic Anchor Systems," *Journal of Composites for Construction*, Vol. 12, No. 1, 2008, pp. 35~43.

15. Kim, Y. J., Wight, R. G., and Green, M. F., "Flexural Strengthening of RC Beams with Prestressed CFRP Sheets: Using Non-Metallic Anchor Systems," *Journal of Composites for Construction*, Vol. 12, No. 1, 2008, pp. 44~52.

16. De Lorenzis, L. and Teng, J. G., "Near-Surface Mounted FRP Reinforcement: an Emerging Technique for Strengthening Structures," *Composites Part B: Engineering*, Vol. 38, No. 2, 2007, pp. 119~143.