

Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates

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Abstract: It is an effective way to improve the flexural behavior of reinforced concrete (RC) members by externally bonded carbon fiber reinforcement polymer (CFRP) laminates on the soffit of the members. However, there is little investigation on flexural performance of RC beam flexurally strengthened by side-bonded FRP laminates. To investigate the flexural behavior of RC beams side-bonded CFRP laminates and the difference of RC beams strengthened by soffit-bonded and side-bonded CFRP laminates, a total of 8 CFRP-strengthened beams and 1 control beam were tested. The experimental results show that: 1) the first crack loads of RC beams strengthened by side-bonded CFRP laminates are much higher than that of RC beams strengthened by soffit-bonded CFRP laminates. The first crack loads of side-bonded CFRP laminates beams improved significantly; 2) Side-bonded and soffit-bonded CFRP laminates have almost the same effect on the flexural stiffness of RC beams strengthened with same quantity of CFRP laminates before tension rebar yielding. However, side-bonded CFRP laminates can affect crack width and crack pattern of the strengthened beams, and the pre-crack stage of RC beam by side-bonded CFRP laminates extended remarkably. 3) different to soffit-bonded CFRP laminates RC beams, side-bonded CFRP laminates cannot improve the first yielding and the ultimate load bearing capacity of RC beams.

Keywords: RC beam, side-bonded, CFRP, flexural performance.

INTRODUCTION

Externally bonded FRP laminates on the soffit of RC beams is an effective way in flexural strengthening. However, there is little investigation on flexural behavior of RC beam by side-bonded CFRP laminates. Zhang *et al.*, [1] investigated the flexural behavior of four under-reinforced concrete beams strengthened by side-bonded CFRP laminates. Oehler *et al.*, [2] and Mohamed Ali *et al.*, [3] concluded that FRP side plated beams, in some situations, was a better option than FRP tension face plated beams as they can achieve higher strength and ductility.

To investigate the flexural behavior of side bonded CFRP laminates RC beams and the difference of flexural behavior between soffit-bonded and side-bonded CFRP laminates RC beams, this paper presents experimental study to investigate the flexural behavior of RC beams by side-bonded and soffit-bonded CFRP laminates.

EXPERIMENTAL PROGRAM

6 side-bonded CFRP sheets RC beams, 2 soffit-bonded beams, and 1 control beam were tested. Fig. (1) shows the dimension and reinforcement arrangement of specimen. The test set-up and instrumentation locations are shown in Fig. (2). According to the design provisions provided by

CECS146-2003 [4], all strengthened beams were designed to be failed by flexural failure in order to investigate their flexural behavior. The test variables included number of ply of CFRP laminates, bonding configuration of CFRP laminates and anchor program of CFRP laminates at beam-column joint. As shown in Fig. (3a-c), two kinds of anchor programs were used to anchor CFRP laminates for the side-bonded beams, one is flexible anchor (denoted by F), and the other is rigid anchor (denoted by R); Fig. (3d) shows the anchorage of soffit-bonded CFRP laminate beams at the joint. The bonding configuration and amount of CFRP laminates are shown in Fig. (3e). Table 1 lists the CFRP sheets configuration of each specimen.

Ready-mixed concrete with cube compressive strength 55.8 MPa was used. The properties of CFRP laminate, with ultimate tensile strength 4 150 MPa, Young's modulus 235 GPa, and nominal thickness 0.111 mm, were provided by the manufacturer. The ultimate tensile strength of tension rebar is 380 MPa, and its Young's modulus is 200 GPa.

TEST RESULTS AND ITS ANALYSIS

Table 2 summarizes the characteristic load and failure modes of all test beams. Figs (4 and 5) show the comparisons of load-deflection behaviors of side-bonding, soffit bonding and control beams. As the soffit bonding CFRP laminates beams, Side-bonding FRP laminates can also improve the flexural behavior of RC beams. However, it is obviously that the flexural behavior of the beams with side-bonding CFRP laminates is worse than that of the beams by soffit bonding, and the flexural behavior of the

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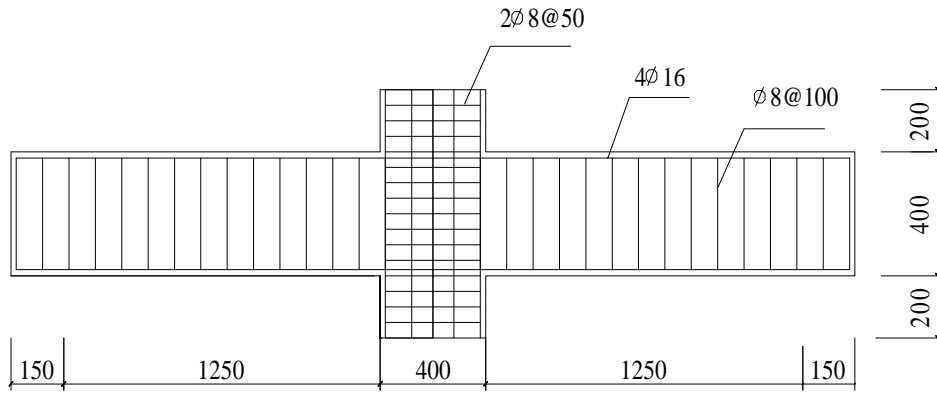


Fig. (1). Dimension and reinforcement arrangement.

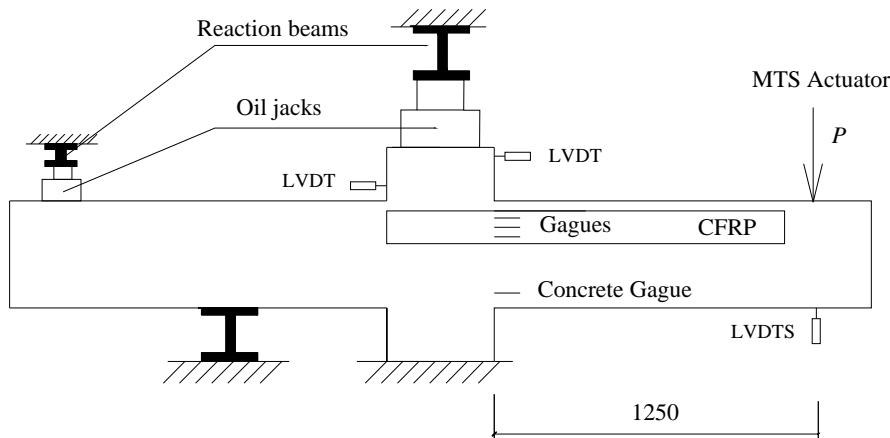


Fig. (2). Test setup and instrumentation arrangements.

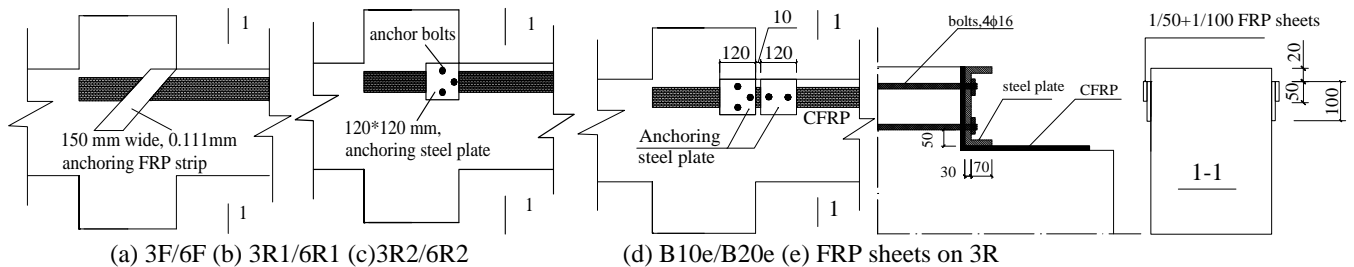


Fig. (3). Anchor method of CFRP laminates at the joint and amount of FRP sheets.

strengthened beams with rigid anchor of CFRP laminates is better than that of the beams with flexible anchor.

ANALYSIS OF CHARACTERISTIC LOADS

First Crack Load

It has been demonstrated that soffit bonding FRP laminates has little effect on the first crack load of the strengthened RC beams [5, 6]. However, as shown in Fig. (6), it is evident that side-bonding FRP laminates can significantly improve the first crack load of the strengthened beams. Compared to the first crack load of the control beam, the first crack load of beam 3F, 3R1, and 3R2 had an increase by 36%, 42%, and 37%, respectively. The first crack load of beam 6F, 6R1, and 6R2 had a significantly increase by 79%, 79%, and 77%, respectively. The first

Table 1. Specimen

Beam	CFRP Sheets
BC	Control beam
3F	2/75
3R1	1/50+1/100
3R2	1/50+1/100
B10e	1/300
6F	4/75
6R1	2/50+2/100
6R2	2/50+2/100
B20e	2/300

Table 2. Summary of Test Results (kN)

Beam	P_{cr}^1	P_y	P_u	$P_{\text{strengthened beam}}/P_{BC}^2$			Failure Mode
BC	25.2	87.6	91.4	-	-	-	flexural failure
3F	34.2	89.0	100.3	1.36	1.02	1.10	anchor failure
3R1	35.8	90.7	105.2	1.42	1.04	1.15	FRP debonding
3R2	34.5	91.0	104.2	1.37	1.04	1.14	FRP debonding
B10e	25.5	104.3	113.9	1.01	1.19	1.25	FRP debonding
6F	45.2	97.5	106.5	1.79	1.11	1.17	anchor failure
6R1	45.1	90.2	104.2	1.79	1.03	1.14	anchor failure
6R2	44.5	95.1	106.0	1.77	1.09	1.16	anchor failure
B20e	25.9	107.5	123.0	1.03	1.23	1.35	FRP debonding

1- P_{cr} , P_y , and P_u denote first crack load, first yield load, and ultimate load, respectively; 2-ratio of the characteristic load of the strengthened beam to that of the control beam.

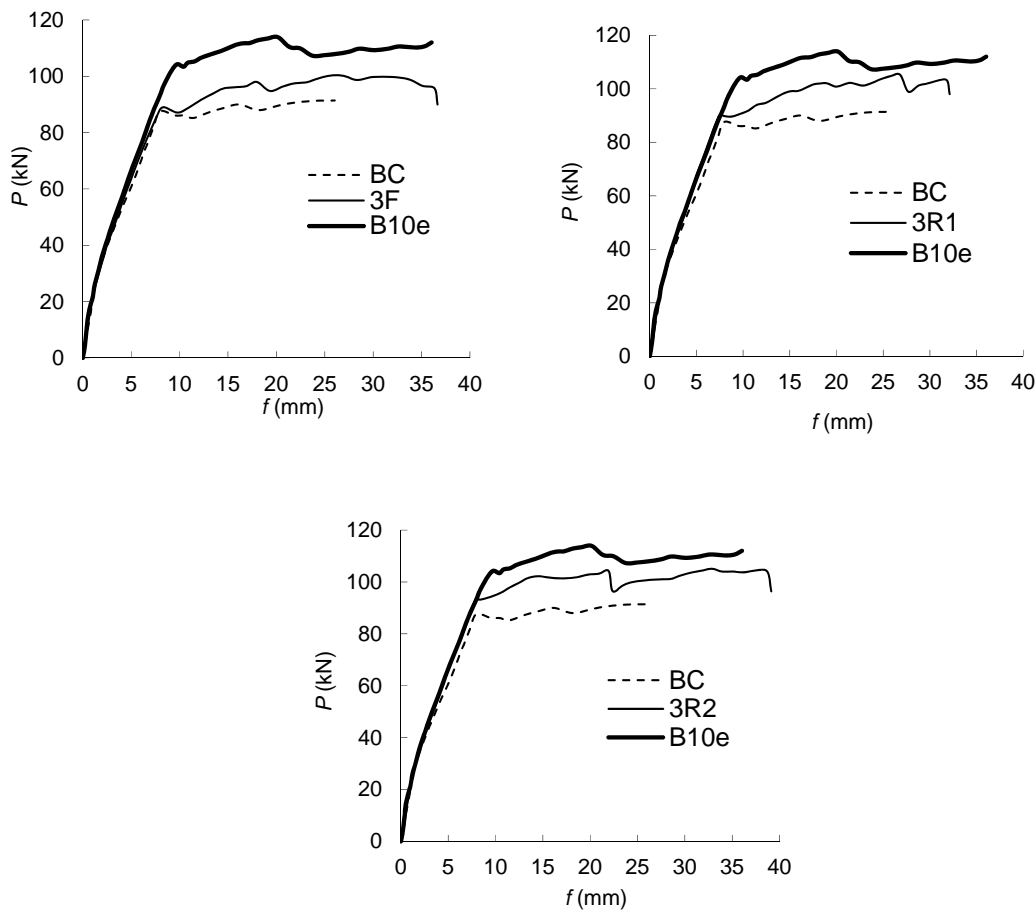


Fig. (4). Comparison of load-deflection relationships among beams BC, B10e, and 3F(3R1, 3R2).

crack load of Beam B10e and B20e is 25.5 kN and 25.9 kN, respectively, which are almost the same with that of the control beam.

The present results verified that side-bonding FRP laminates could make a great contribution to confine concrete from premature cracking, this led to the first crack

strength of RC beam improved significantly. According to the test results, there are three experimental phenomena can be employed to explain this result. Firstly, as shown in Fig. (7a, b), the amount of cracks in the side-bonding beams is more than that in the control beam. These cracks spaced uniformly at about 100~150 mm which is less than that in

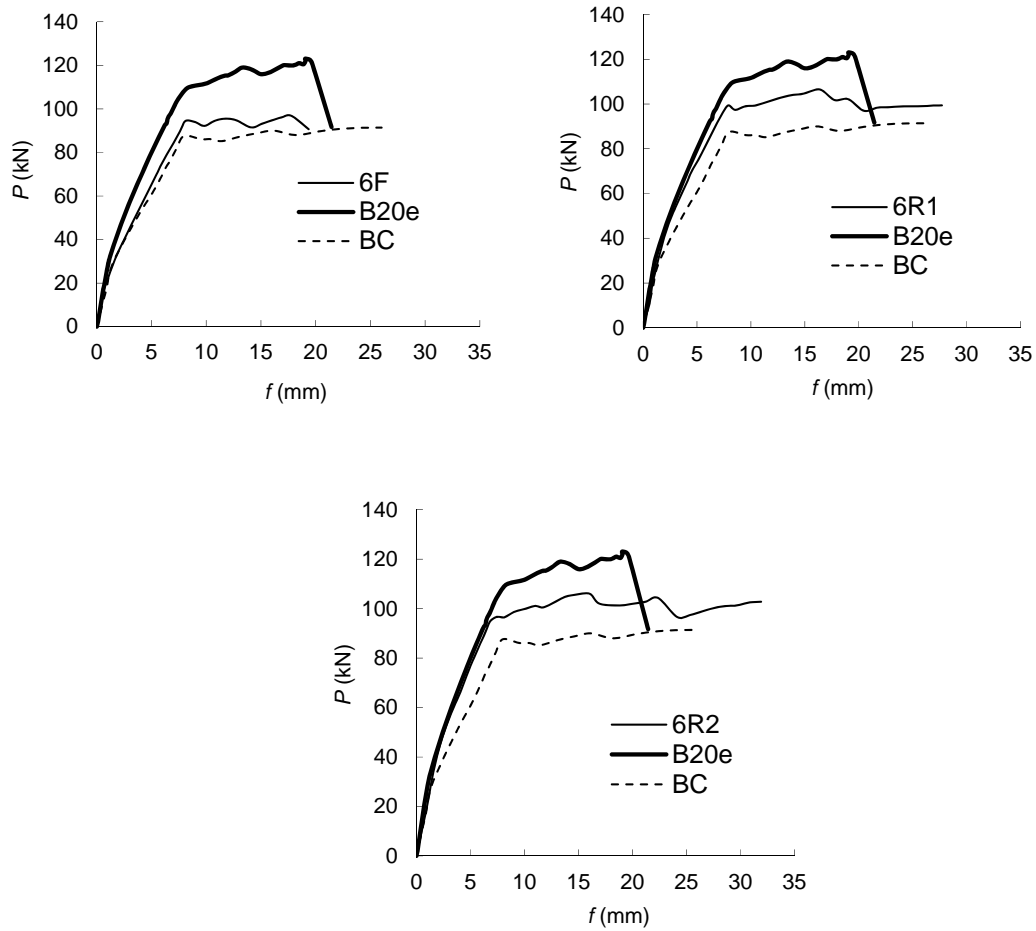


Fig. (5). Comparison of load-deflection relationships among beams BC, B20e, and 6F(6R1, 6R2).

the control beam about 200 mm. Secondly, there are many smeared hairline cracks distributed on the soffit surface of the beam as shown in Fig. (7c, d). The two results indicate that tensile strain in concrete section distributes more uniformly in side-bonding FRP sheets RC beams. Thirdly, the strains in tensile rebar are within the range of 427~598 $\mu\epsilon$, that is, the stress of the tensile rebar is about 85~120 MPa at the first crack load which is about 2~3 times of that of the control beam. All the results exhibit that the mechanical properties of side-bonding FRP sheets beams is like a sort of fiber reinforced concrete and external prestressed concrete.

First Yield Load

Compared with the first yield load of the control beam, the first yield load of beam 3F, 3R1, and 3R2 had an increase by 2%, 3%, and 6%, respectively, and the first yield load of beam 6F, 6R1, and 6R2 had increase by 8%, 11%, and 9%, respectively. This result shows that the anchor methods have almost no effect on the first yield load of the strengthened beams, and this result shows explicitly in Fig. (8). Moreover, side-bonding FRP laminates has not significantly improved the first yield load of the strengthened beams. However, the first yield load of beam B10e and B20e had an increase by 19% and 23%, respectively, which are much higher than that of the side-bonding beams.

Ultimate Load

Compared with the ultimate load of the control beam, the ultimate load of beam 3F, 3R1, and 3R2 had increase by 10%, 15%, and 14%, respectively, and the ultimate load of beam 6F, 6R1, and 6R2 had increase by 6%, 17%, and 16%, respectively. The result shows that the ultimate load of

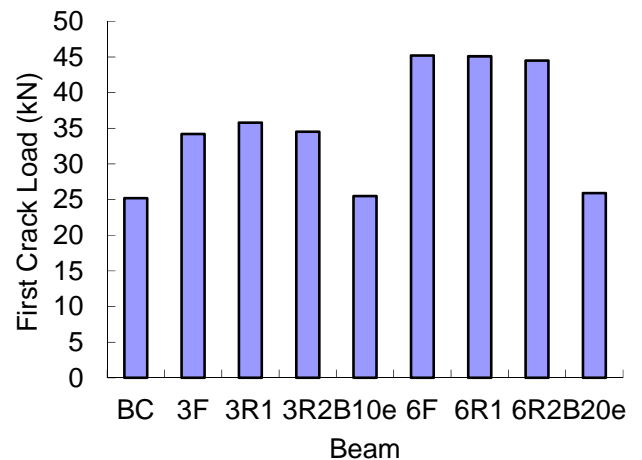


Fig. (6). Comparison of first crack loads of the test beams.

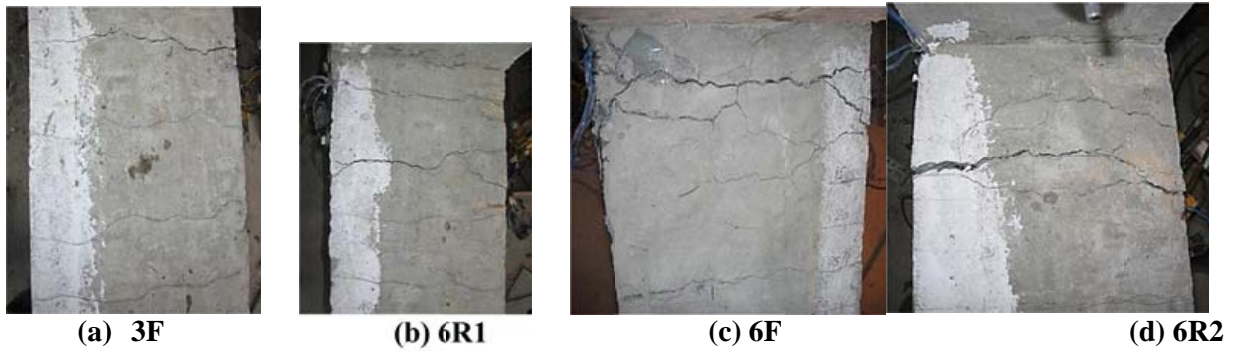


Fig. (7). Cracking characteristics on beams 3F, 6R1, 6F, and 6R2.

the strengthened beams with flexible anchor is less than that of the ones with rigid anchor when the strengthening amount of FRP laminates is constant. Similar to the first yield load, side-bonding FRP laminates also had not significantly improved the ultimate load of the strengthened beams. However, the ultimate load of beam B10e and B20e had an increase by 25% and 35%, respectively, which are two times of that of the side-bonding beams. Fig. (9) illustrates the comparison of the ultimate load of the tested beams.

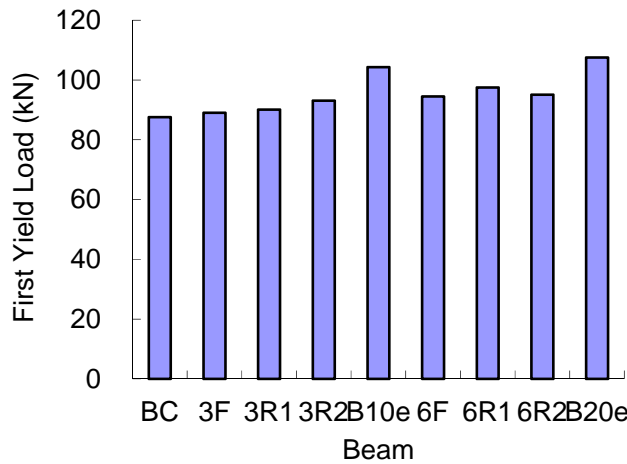


Fig. (8). Comparison of first yield loads of the test beams.

ANALYSIS OF FLEXURAL STIFFNESS AND CRACK WIDTH

Analysis of Flexural Stiffness

The deflection of the side-bonding beams is much bigger than that of the control beam at the first crack load. The flexural stiffness analysis of strengthened beams is summarized in Table 3. At first crack load, the deflection of the control beam is 1.50 mm. The deflection of the side-bonding beams is in the range of 1.96-2.85 mm. Compared to the control beam, the deflection of beam 3F, 3R1, and 3R2 had an increase by 53%, 32%, and 31%, respectively; the increase of beam 6F, 6R1, and 6R2 is 63%, 90%, and 69%, respectively. Therefore, side-bonding FRP laminates can

significantly elongate the pre-crack stage of the strengthened beam.

At the precrack stage, the average of the flexural stiffness of beam 3F, 3R1, and 3R2 to that of the control beam is 1.04 with coefficient of variation 0.03, the average of the flexural stiffness of beam 6F, 6R1, and 6R2 to that of the control beam is 1.03 with coefficient of variation 0.07. At the post-crack stage, the average of the flexural stiffness of beam 3F, 3R1, and 3R2 to that of the control beam is 0.98 with coefficient of variation 0.05; the average of the flexural stiffness of beam 6F, 6R1, and 6R2 to that of the control beam is 1.07 with coefficient of variation 0.10. At the post-yield stage, the average of the flexural stiffness of beam 3F, 3R1, and 3R2 to that of the control beam is 3.64; the average of the flexural stiffness of beam 6F, 6R1, and 6R2 to that of the control beam is 5.87.

The average of the flexural stiffness of beam 3F, 3R1, and 3R2 is 17.54 kN/mm and the flexural stiffness of beam B10e is 18.21 kN/mm at precrack stage; 17.29 kN/mm and 16.50 kN/mm at the postcrack stage. The average of the flexural stiffness of beam 6F, 6R1, and 6R2 is 9.41 kN/mm and the flexural stiffness of beam B20e is 9.54 kN/mm at precrack stage; 10.27 kN/mm and 10.89 kN/mm at the postcrack stage. This indicates that side-bonding and soffit-bonding methods have the same effect on the flexural

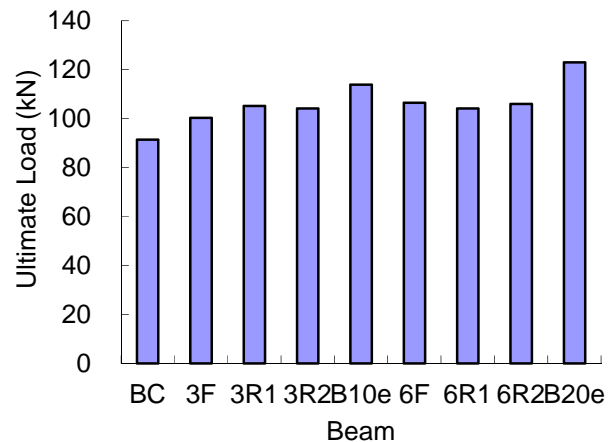


Fig. (9). Comparison of ultimate loads of the test beams.

Table 3. Flexural Stiffness Analysis of Strengthened Beams

Beam	Deflection (mm)			Stiffness(kN/mm)			Stiffness Variation Compared to Control Beam		
	δ_{cr}	δ_y	δ_u	$0-P_{cr}$	$P_{cr}-P_y$	P_y-P_u	$0-P_{cr}$	$P_{cr}-P_y$	P_y-P_u
BC	1.50	7.98	26.03	16.80	9.63	0.21	1.00	1.00	1.00
3F	2.02	8.27	26.80	16.93	8.77	0.61	1.01	0.91	2.90
3R1	1.98	7.47	26.82	18.08	10.00	0.75	1.08	1.04	3.56
3R2	1.96	7.93	21.96	17.60	9.46	0.94	1.05	0.98	4.47
B10e	1.40	9.86	20.15	18.21	9.31	0.93	1.08	0.97	4.43
6F	2.45	7.93	17.56	18.45	9.54	0.93	1.10	0.99	4.44
6R1	2.85	7.56	16.40	15.82	9.58	1.58	0.94	0.99	7.52
6R2	2.53	6.86	16.05	17.59	11.69	1.19	1.05	1.21	5.63
B20e	1.57	9.06	20.62	16.50	10.89	1.34	0.98	1.13	6.37

stiffness of RC beams with same quantity of CFRP laminates before tension steel rebar yielding, this can be easily found in Figs. (10 and 11). As shown in Fig. (12), the flexural stiffness of RC beams can also be significantly improved by side-bonded CFRP laminates.

increased rapidly after concrete cracking. As a result, the stress in the anchoring FRP laminates also increased. Soon after the tension rebar yield, the anchoring FRP laminates

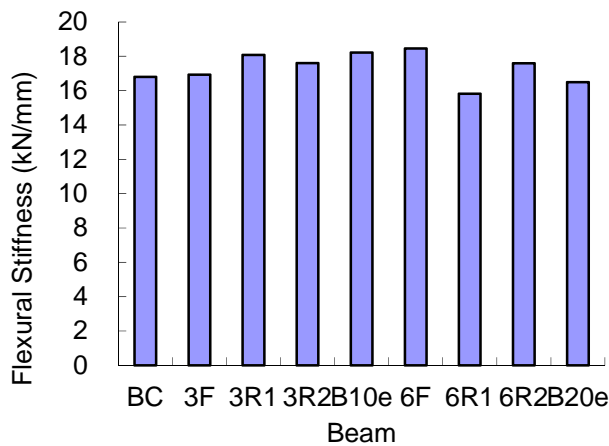


Fig. (10). Flexural stiffness of test beams at precrack stage.

Analysis of Crack Width

The maximum crack width of beam 6F, 6R1, and 6R2 is 0.15, 0.15, and 0.20 mm at the first yield load, respectively, which is much smaller than that of the control beam, 0.30 mm; B10e 0.35 mm; B20e 0.25 mm. Furthermore, at the load 91.4 kN which is the ultimate load of the control beam, the maximum crack width of these beams is only 0.1-0.2 mm, but the crack width of the control beam is 3.4 mm, and there are two cracks exceed 3.0 mm. This indicates that side-bonding FRP laminate can effectively decrease the crack width of the strengthened beams.

Analysis on Anchor Program

In the flexible anchored beams 3F and 6F, the tensile stress in the side-bonded FRP laminates at the critical section

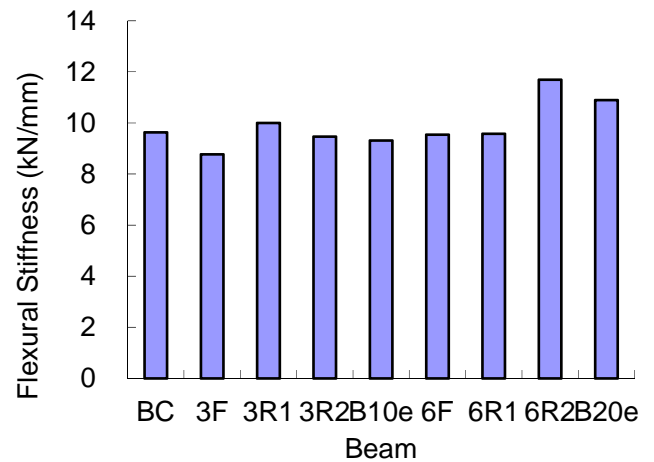


Fig. (11). Flexural stiffness of test beams at postcrack stage.

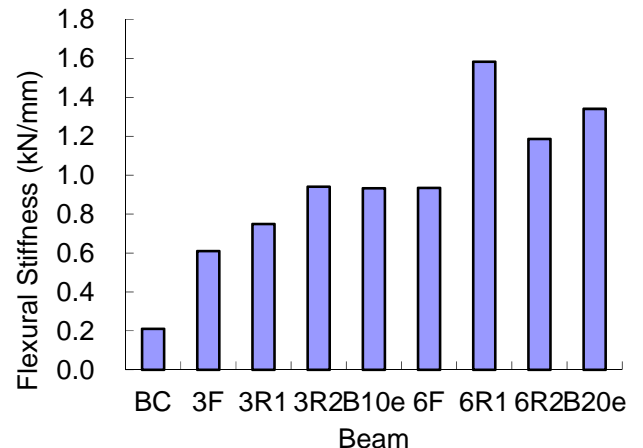


Fig. (12). Flexural stiffness of test beams at postyield stage.

were tore into strips gradually, and then the side-bonded FRP laminates were out of work at the post yield stage. In the rigid anchor beams 3R and 6R, the main failure mode was concrete crush tensioned by the anchor bolts. According to the analytical results of the characteristic loads of the test beams as shown in Table 2 and Fig. (5), it can be concluded that the rigid anchor program is better than the flexible anchor program.

CONCLUSIONS

This paper carried out an experimental study on the flexural performance of RC beams side-bonded and soffit-bonded FRP laminate. The following conclusions can be drawn:

- 1) side-bonded and soffit-bonded CFRP laminates have almost the same effect on the flexural stiffness of RC beams strengthened by same quantity of CFRP laminates before tension rebar yielding. However, side-bonded CFRP laminates can affect crack width and crack pattern of the strengthened beams, and the pre-crack stage of RC beam side-bonded CFRP laminates extended remarkably.
- 2) side-bonded CFRP laminates can also improve the flexural behavior of RC beams, and the first crack loads of RC beams side-bonded CFRP laminates are much higher than that of RC beams soffit-bonded CFRP laminates. Like fiber reinforced concrete, side-bonded CFRP laminates can significantly improve the first crack strength of RC beams.
- 3) the first yielding load and the ultimate load of RC beam side-bonded CFRP laminates cannot be improved significantly as that of soffit-bonded CFRP laminates beams. This indicates that it would be best not to use

side-bonded FRP laminates to improve the ultimate flexural capacity of RC beam.

CONFLICT OF INTEREST

Declared none.

ACKNOWLEDGEMENTS

The research program discussed in this paper was funded by the Ministry of Housing and Rural-Urban Development of PRC (2009-K2-39) and the National High Technology Research and Development Program of China (863 Program, No. 2007AA04Z437).

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Received: November 24, 2011

Revised: November 30, 2011

Accepted: December 15, 2011

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