Experimental Study on Flexural Behaviour of Pre-damaged Reinforced Concrete Beams Strengthened with CFRP

XIE JIAN-HE, GUO YONG-CHANG*, LIU YI-FENG, CHEN GONG-FA
Guangdong University of Technology, Faculty of Civil and Transportation Engineering, 100 Waihuan Xi Road, Higher Education Mega Center, Guangzhou 510006, China

An experimental study was conducted to investigate the flexural behaviour of the pre-damaged reinforced concrete (RC) beams strengthened with carbon fiber reinforced polymer (CFRP). 25 beams with the size of 2200mm×150mm×200mm (length, width and height) were tested to bending loads. The parameters of the investigation included two pre-damage levels of RC beam, four shear span-depth ratios and two CFRP thicknesses. The effects of these parameters were analyzed on the failure modes, load carrying capacity, flexural stiffness and midspan CFRP strain of the strengthened beams. The results show that CFRP can significantly improve the flexural load carrying capacity of load-damaged RC beams. The pre-damage level has no obvious effects on the flexural behaviour of the strengthened RC beams with CFRP. With the decrease of the shear span-depth ratio, the failure mode of the strengthened beams may transform from debonding induced by intermediate crack (IC) to cover separation near CFRP end. For the strengthened beams failed by IC debonding, more CFRP can provide the higher load carrying capacity and flexural stiffness, but it is not the case for the beams failed by cover separation near CFRP end.

Keywords: Carbon Fiber reinforced polymer (CFRP), Strengthening˙Pre-damage, Reinforced Concrete (RC), Shear span-depth ratio, Debonding

In recent years, it has become increasingly common to strengthen reinforced concrete (RC) structures by bonding externally carbon fiber reinforced polymer (CFRP) laminates. CFRP is of interest to rehabilitation engineers because of the high strength/weight ratio, ease of handling and application, the elimination of the need for heavy equipment, a fast construction rate and the fact that they do not corrode [1-3]. Extensive studies on the flexural behaviour of the RC beams strengthened with CFRP have been conducted. However, most of these studies mainly focused on the use of CFRP sheet for the repair of virgin beams [3-7]. In fact, for the most part of concrete structures, the in-service components usually work with flexural cracks. Therefore, the study on the mechanical properties of pre-damaged RC beams with CRFP close to the actual state of the in-service components may have more reference value.

With regard to the flexural properties of load-damaged RC beams repaired with CRFP, some experimental studies were reported [8-14]. Wang and Li [8], Shin et.al [9,10] , Arduini and Nanni [11], Shahawy et al. [12] , Bonacci and Maalej [13]focused on the effect of sustaining loads on the flexural behaviour of repaired RC beams. In their experiments, most tested beams were maintained the loading during the application and curing of the FRP. The experimental results of Arduini and Nanni [11] showed that the specimen repaired under sustaining vertical loads had an average strength decrease of 8% over the specimen repaired without sustaining loads. It was mainly because the initial flexural cracks of the beams under sustaining loads could not be cured after strengthening, resulting in weakening the strengthening effectiveness. Thus, if possible the damaged RC beams should be repaired with CFRP after unloading. Fayyadh and Abdul Razak [14] conducted an experiment on four RC beams to study the effects of different pre-damage levels on the effectiveness of repairing the pre-damaged beams with CFRP. Their results prove the effectiveness of the CFRP sheets as a repair technique which increases the flexural stiffness and the ultimate load capacity whatever the pre-damage levels [14]. It should be mentioned that the amount of tested specimens were few in these reported experiments, resulting in that some parameters were not taken into account in these studies, such as shear span-depth ratio. It is well known that shear span-depth ratio could affect the failure mode of beam, indicating that the effectiveness of CFRP strengthening on the damaged beam would change with shear span-depth ratio.

The present work is geared toward evaluating the use of CFRP laminates to repair load-damaged RC beams—a practical application that has not received enough attention in experimental research. In this paper, the effects of different pre-damage levels, shear span-depth ratio and CFRP thickness are investigated on the flexural behaviour of damaged RC beams strengthened with CFRP. The remaining part of this paper is organized as follows. Section I starts out with an introduction of the experimental set-up including concrete beam-geometry, reinforcement details, basic properties of the materials used and loading scheme, Section II outlines and discusses the experimental results including failure mode, flexural load carrying capacity, load-deflection relationship and CFRP strain variation, Section III outlines the conclusion of this experimental study.

Experimental part

Totally 25 RC beams with the size of 2200mm ×150mm×200mm (length, width and height) were tested in this study. The typical geometry and reinforcement of the beams are shown in figure 1. The specimens were made from ordinary portland cement. The concrete cube compressive strength is 34.7 MPa. The main steel exhibited a yield strength of 354 MPa and an elastic modulus of 168 GPa. The elastic modulus of CFRP sheets was 226 GPa, with an ultimate tensile strength of 4361 MPa, and the CFRP sheet has a nominal thickness of 0.167 mm. The width

* *email: yc_guo@yeah.net; Tel.: +86-13538832879*

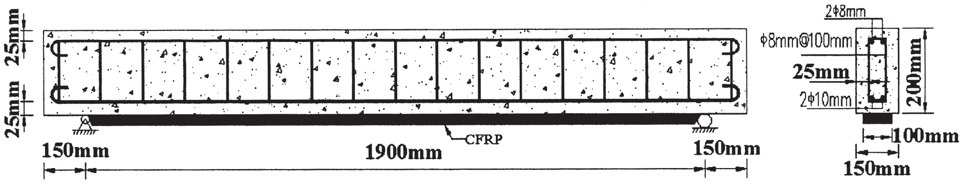


Fig. 1. Beam-geometry, reinforcement details

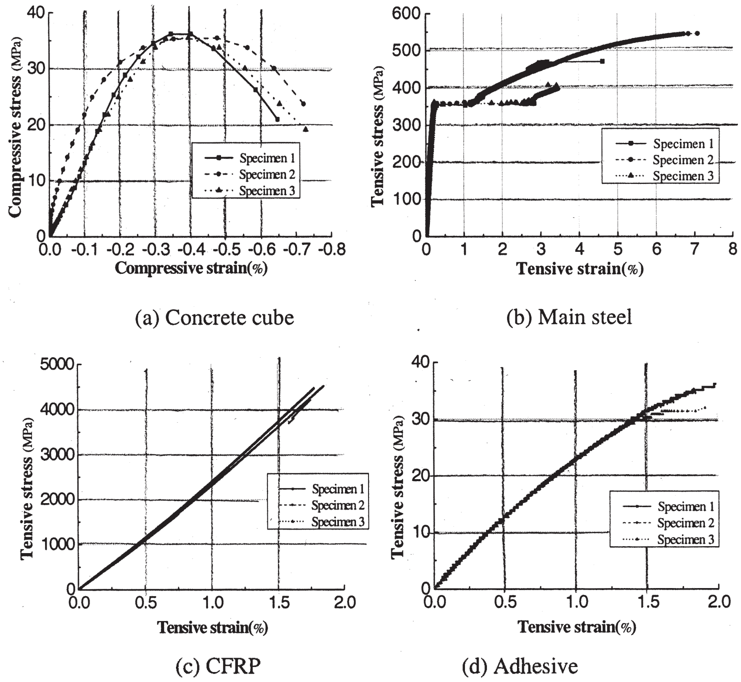


Fig. 2(a, b, c, d). Stress-strain curves of the materials

and longitudinal length of CFRP in all the strengthened beams is 100 mm and 1900 mm, respectively. The adhesive has an ultimate tensile strength of 35.7 MPa and an elastic modulus of 2484 MPa. The stress-strain curves of the above four materials are shown in figure 2.

In this study, three parameters were considered, including pre-damage levels of RC beams, shear span-depth ratio and CFRP thickness. A control beam without CFRP was tested up to failure in one run under three-point loading for comparison. Damage level I was defined as that RC beams under three-point loading are pre-load up to the yield moment of control beam, and damage level II was defined as that RC beams under three-point loading are pre-load up to the specified midspan deflection (9 mm), which is twice as much as that of the control beam at the time of yielding. Also, four different shear span-depth ratio were studied including 6.43, 3.71, 2.57 and 1.43, of which 5.43 is for three-point loading, and the others for four-point loading, as shown in figure 3. The CFRP thickness was used for strengthening RC beams including one layer and two layers. Table 1 shows the number of the beams, the test conditions and results.

Results and discussions

The results of the flexure tests were summarized in table 2, including failure modes, yield load and ultimate load, midspan deflection of the tested beams. The results obtained from these tests were analyzed in the following.

Failure modes

The test results show that the shear span-depth ratio has a significant effect on the failure modes of the strengthened RC beams with CFRP, but it is not the case for pre-damage level and CFRP thickness. The testing revealed the following failure modes for the strengthened RC beams: (1) Intermediate flexural crack induced

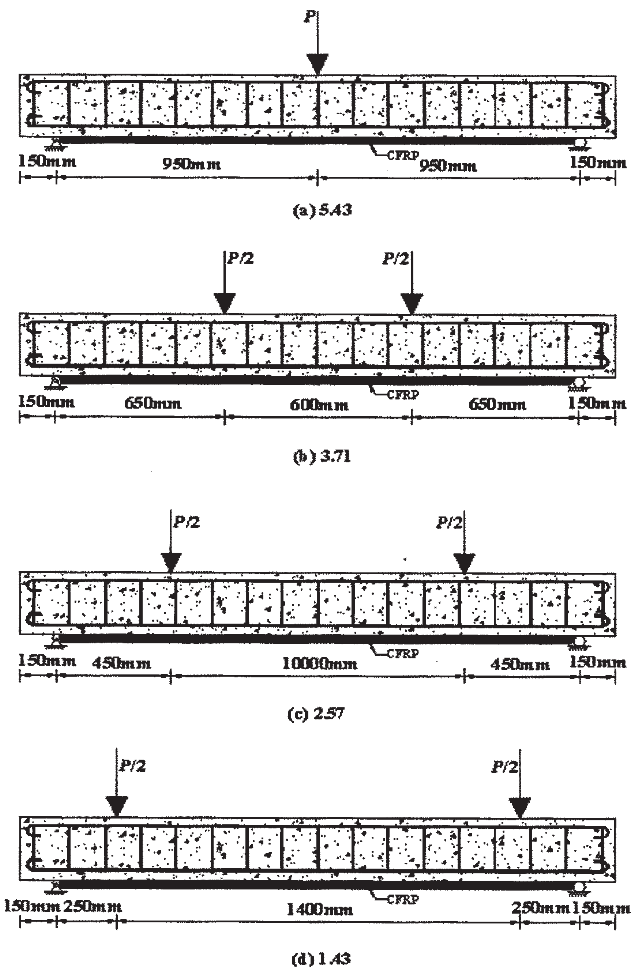


Fig. 3. Four different shear span-depth ratios of the tested beams

Table 1
SUMMARY OF TEST CONDITIONS AND RESULTS

Beam[a]	Damage level	Shear depth ratio	CFRP layer	Yield load P_y (kN)	Ultimate load P_u (kN)	Midspan moment (kN·m) At yield load	Midspan moment (kN·m) At ultimate load	Midspan deflection (mm) At yield load	Midspan deflection (mm) At ultimate load	Failure modes
0L0-0	no	5.43	0	23	29	10.93	13.78	4.50	44.14	tensile steel yield followed by concrete compression crushing
1L0-0	no	5.43	1	31	45	14.72	21.38	5.54	20.30	mode I
1L1-0	level I	5.43	1	30	46	14.25	21.85	4.20	20.63	mode I
1L2-0	level II	5.43	1	31	42	14.72	19.95	5.22	17.63	mode I
1L0-600	no	3.71	1	40	63	13.00	20.48	6.50	25.49	mode II
1L1-600	level I	3.71	1	41	64	13.33	20.80	6.22	25.87	mode II
1L2-600	level II	3.71	1	42	63	13.65	20.48	5.97	24.70	mode II
1L0-1000	no	2.57	1	65	91	14.63	20.48	6.38	24.46	mode II
1L1-1000	level I	2.57	1	63	95	14.18	21.38	6.56	25.13	mode II
1L2-1000	level II	2.57	1	62	92	13.95	20.70	6.99	24.75	mode II
1L0-1400	no	1.43	1	145	170	18.12	21.25	8.52	14.11	mode III
1L1-1400	level I	1.43	1	150	156	18.75	19.50	8.24	10.25	mode III
1L2-1400	level II	1.43	1	140	161	17.50	20.12	8.67	14.86	mode III
2L0-0	no	5.43	2	33	54	15.68	25.65	5.28	17.25	mode I
2L1-0	level I	5.43	2	31	53	14.72	25.18	4.98	20.25	mode I
2L2-0	level II	5.43	2	33	53	15.68	25.18	5.28	16.88	mode I
2L0-600	no	3.71	2	47	69	15.28	22.43	6.38	17.63	mode II
2L1-600	level I	3.71	2	47	74	15.28	24.05	6.19	21.39	mode II
2L2-600	level II	3.71	2	45	69	14.63	22.43	6.19	17.25	mode II
2L0-1000	no	2.57	2	69	107	15.52	24.08	7.35	21.07	mode II
2L1-1000	level I	2.57	2	71	111	15.98	24.98	7.05	22.44	mode II
2L2-1000	level II	2.57	2	71	103	15.98	23.18	7.24	18.85	mode II
2L0-1400	no	1.43	2	124	135	15.50	16.88	6.99	10.02	mode III
2L1-1400	level I	1.43	2	122	133	15.25	16.62	6.75	9.25	mode III
2L2-1400	level II	1.43	2	—	159	—	19.88	—	9.51	mode III

Note [a]xLy-z = layers of fiber reinforced polymer (FRP) sheets where x = 0,1,2 and y = damage level; z = distance between the load point, 0 means three-point loading. Failure mode I is that intermediate flexural crack induced debonding. Failure mode II is that flexural-shear crack induced debonding and cover separation. Failure mode III is cover separation near CFRP end.

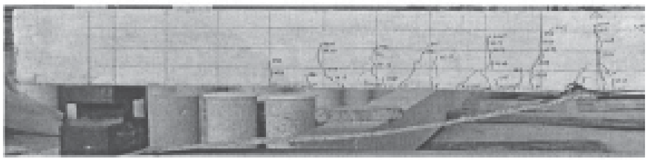
debonding (Mode I). (2) Flexural-shear crack induced debonding and cover separation (Mode II). (3) Cover separation near CFRP end (Mode III), as shown in figure 4.

For the beams under three-point loading (shear span-depth ratio of 5.43), the failure process is that interfacial crack between CFRP and concrete initiated at the root of the main flexural crack, and as the load increased, CFRP debonding develops from the middle to the CFRP end, the failure mode is shown in figure 4(a) . For the beams of 3.71 and 2.57 shear span-depth ratio, interfacial crack initiated at the root of the main flexural-shear crack below the loading point. As the load increased, the interface crack propagated to the CFRP end, and the main flexural-shear crack developed along concrete cover at the level of tension reinforcement, resulting in that CFRP debonding and cover separation occurred, as shown in figure 4(b) and figure 4(c). According to the failure causation, failure mode I and mode II can be collectively referred to as intermediate crack (IC) debonding. For the beams of 1.43 shear span ratio, their failure was due to the main shear crack near the CFRP end. With the increase of load, the main shear crack developed to the tension reinforcement and propagated along the concrete cover, leading to concrete cover peeling, as shown in figure 4(d). It can be concluded that with the decrease of the shear span ratio, the failure modes of the strengthened beam had a transform from intermediate crack debonding to cover separation near CFRP end.

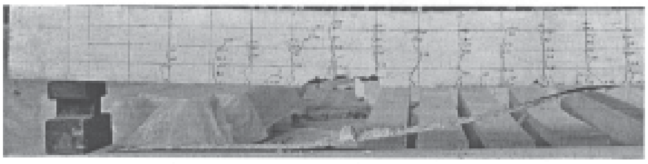
Flexural load carrying capacity

The yield load and ultimate load of the tested beams are shown in table 1 and figure 5. In this paper, the load-carrying capability is defined as the midspan moments at the ultimate load of the beams. It can be seen from figure 5 that, for the beams with the same shear span-depth ratio and CFRP thickness, the pre-damage level had a minor impact on the yielding load and ultimate load, as reported by Fayyadh and Abdul Razak [14].

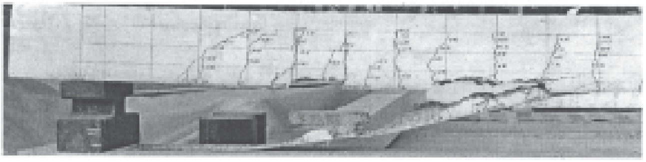
With regard to the effects of CFRP thickness on the flexural load carrying capacity of the strengthened beam,



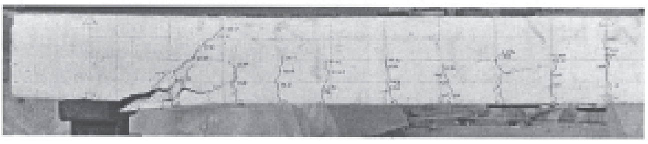
(a) Shear span-depth ratio of 5.43 (Specimen 1L0-0)



(b) Shear span-depth ratio of 3.71 (Specimen 1L0-600)



(c) Shear span-depth ratio of 2.57 (Specimen 1L0-1000)

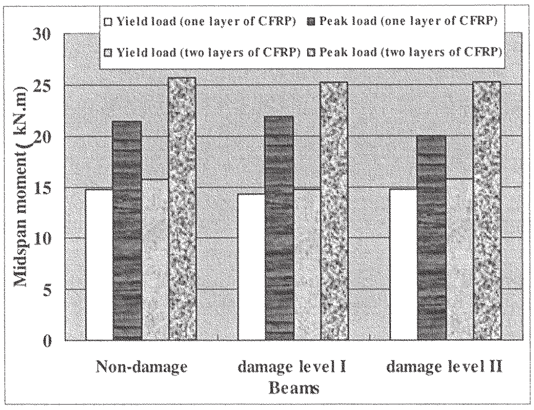


(d) Shear span-depth ratio of 1.430 (Specimen 2L1-1400)

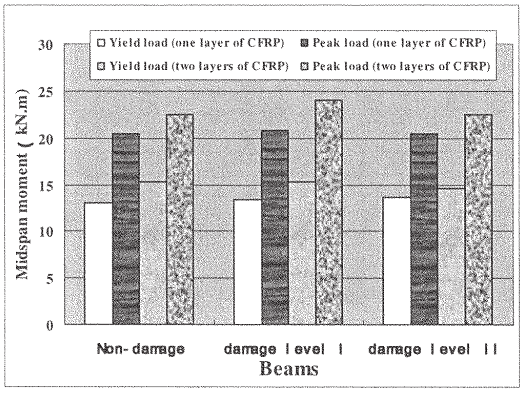
Fig. 4(a, b, c, d). Failure modes

figure 5(a) shows that when the shear span-depth ratio was 5.43, compared with one layer of CFRP, two layers of CFRP improve the ultimate loads by 9.5, 15.6 and 9.5% for non-damage beams, beams with damage level I and beams with damage level II, respectively. Figure 5(b) shows that when the shear span-depth ratio was 3.71, compared with one layer of CFRP, two layers of CFRP improve the ultimate loads by 17.6, 16.8 and 12.0% for non-damage beams, beams with damage level I and beam with damage level II, respectively. Figure 5(c) shows that when the shear span-depth ratio was 2.57, compared with one layer of CFRP, two layers of CFRP improve the ultimate loads by 17.6, 16.8 and 12.0% for non-damage beams, beams with damage level I and beams with damage level II, respectively. Figure 5(d) shows that when the shear span-depth ratio was 1.43, compared with one layer of CFRP, two layers of CFRP improve the ultimate loads by 20.6, 14.8 and 1.2% for non-damage beams, beams with damage level I and beams with damage level II, respectively. From these results, it can be concluded that for the beams failed by debonding, more layers of CFRP can provide the higher load carrying capacity, but it is not the case for the beams failed by cover separation near CFRP end. It is mainly because the stress concentration near the CFRP end becomes more serious with the increase of CFRP thickness, as reported by Shin et.al [9].

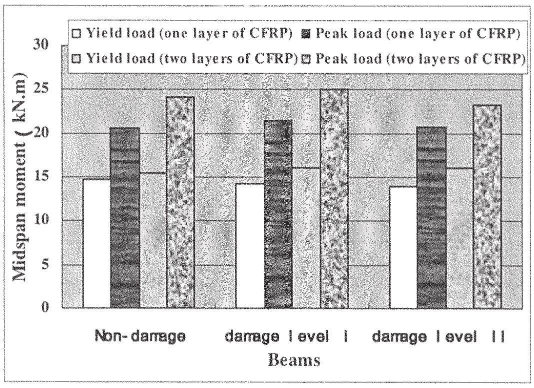
In addition, it can be found from table 1 that the yield load and ultimate load of the strengthened beams have a significant increase with the decrease of the shear span-depth ratio. However, it is should be mentioned that when the shear span-depth ratio was 5.43, 3.71 and 2.57, the load carrying capability of the beams were close, but higher than that of the beams whose shear span-depth ratio is 1.43. This is because that the beams whose shear span-depth ratio are 5.43, 3.71 and 2.57 occurred the similar failure (intermediate debonding), which were mainly controlled by the midspan moment of the beams, but the beams failed by cover separation near CFRP end (shear span-depth ratio of 1.43) were mainly controlled by the shear force of the beams near CFRP end. Thus, it indicates that when the shear span ratio is more than 2.5, the strengthened beam has a better load carrying capability.



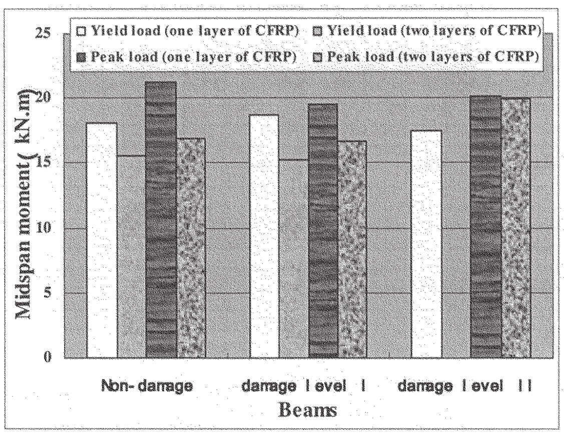
(a) Shear span-depth ratio of 5.43



(b) Shear span-depth ratio of 3.71

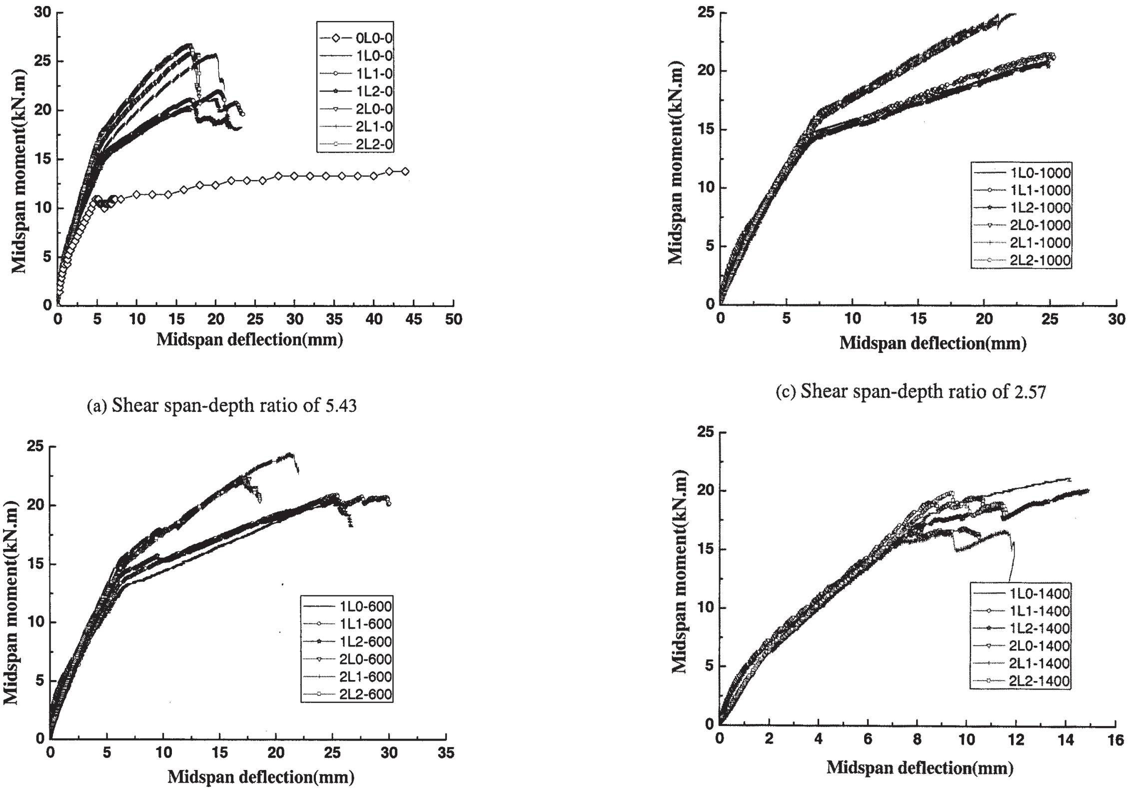


(c) Shear span-depth ratio of 2.57



(d) Shear span-depth ratio of 1.43

Fig. 5(a, b, c, d). Yield load and ultimate load of the tested beams



(a) Shear span-depth ratio of 5.43

(c) Shear span-depth ratio of 2.57

(b) Shear span-depth ratio of 3.71

d) Shear span-depth ratio of 1.43

Fig. 6(a, b, c, d). Curves of midspan moment and deflection

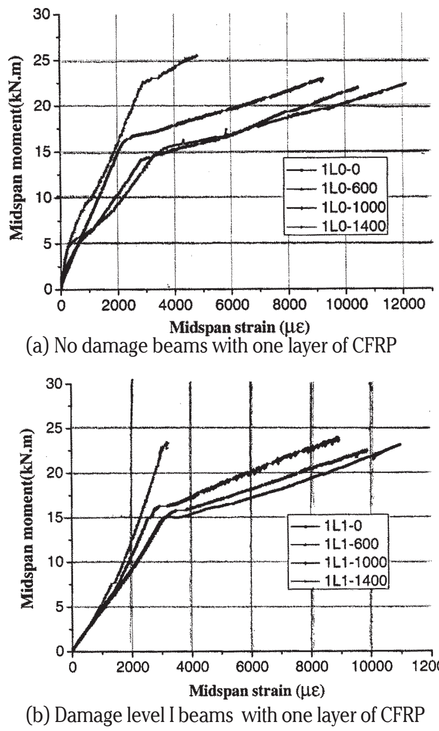
Flexural stiffness

The midspan moment and deflection of the tested beams are shown in figure 6. It can be shown from figure 6(a) that CFRP not only increases the load carrying capacity, but also improves the flexural stiffness for the pre-damaged RC beams. For the beams with the same CFRP thickness and shear span–depth ratio, figure 6 shows that the beams with no pre-damage had an elastic phase before cracking. Before the cracking load, the flexural stiffness of the no damage beams is slightly larger than that of the pre-damage beams. After cracking, the curves of midspan moment and deflection of the beams with no pre-damage is close to that of the pre-damaged beams. It is indicated that the pre-damage level has no obvious effects on the flexural stiffness of the strengthened RC beams.

In addition, when the pre-damage level and shear span ratio were same, it can be seen from figure 6 that compared with two layers of CFRP, one layer of CFRP can provide better ductility for the strengthened beam. Before yielding the curves of the beams with two layers and one layer of CFRP were close, while after yielding the two curves gradually separated, as the tension stresses before yielding were mainly undertaken by the main steels not the CFRP, but after yielding CFRP played a leader role. Moreover, as shown in figure (6a), figure (6b) and figure 6(c), in the phase after yielding the midspan deflection of the beams with two layers of CFRP is smaller than that of the beams with one layer of CFRP. This is because that when the shear span ratio is between 2.57 and 5.43, the failure of the beam originated at the middle section, more CFRP can provide larger effects to resist the propagation of flexural crack. It should be mentioned that when the shear span ratio is 1.43, after yielding the midspan deflection of the beams with two layers of CFRP is larger than that of the beams with one layer of CFRP, as show in figure 6(d). This may be because that the loading point is close to the support, resulting in the main shear crack control the failure, and the increase of the CFRP thickness increase the stress concentration, as previously mentioned.

Relationship between midspan moment and CFRP strain

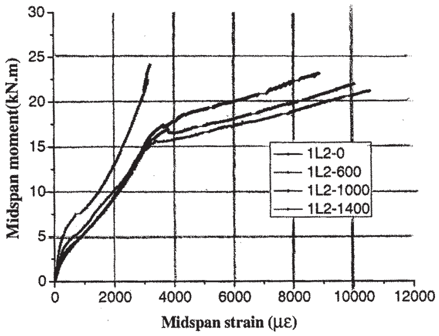
The curves of midspan moment and CFRP strain of the tested beams are shown in figure 7. It can be seen from figure 7 that when the CFRP thickness and pre-damage level were same, the curves of the beams with different shear span-depth ratio gradually separated with the increase of loads. With the increase of the shear span-depth ratio, the CFRP strain of the beams increased. It should be mentioned that the CFRP strain of the beams failed by debonding at the ultimate loads have little difference, but they are much larger than that of the beams failed by cover separation near CFRP end, which indicates



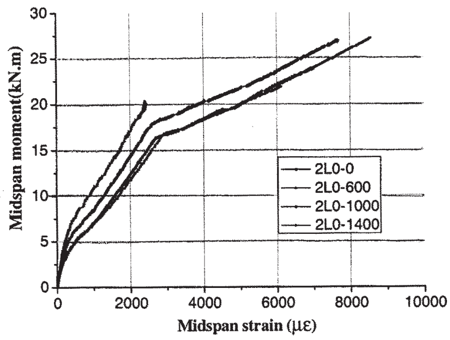
(a) No damage beams with one layer of CFRP

(b) Damage level I beams with one layer of CFRP

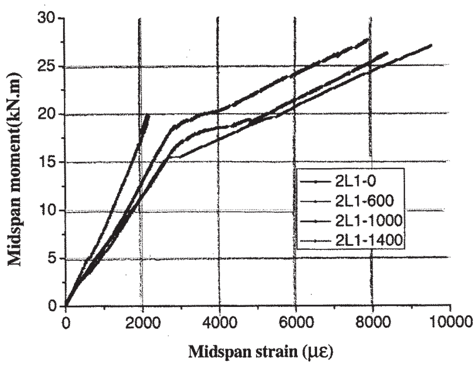
Fig. 7(a, b). Curves of midspan moment and CFRP strain



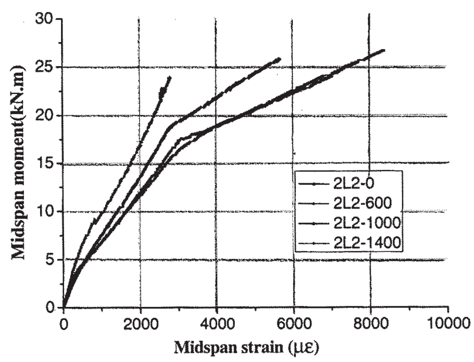
(c) Damage level II beams with one layer of CFRP



(d) No damage beams with two layer of CFRP



e) Damage level I beams with two layer of CFRP



(f) Damage level II beams with two layer of CFRP

Fig.7(c, d, e, f). Curves of midspan moment and CFRP strain

that increasing shear span-depth ratio can improve CFRP utilization.

Conclusions

This study has investigated the effects of pre-damage level, shear span-depth ratio and CFRP thickness on the flexural behavior of pre-damaged RC beams strengthened with CFRP. The following conclusions can be drawn from the experimental results:

- CFRP can significantly improve the flexural load carrying capacity of pre-damaged RC beams. Pre-damage level has no obvious effects on the stiffness, yield loads and ultimate loads of the pre-damaged RC beams with CFRP.;

- the shear span-depth ratio has a significant effect on the failure mode and load carrying capacity of the strengthened RC beams with CFRP. With the decrease of the shear span-depth ratio, the failure mode of the strengthened beams may transform from IC debonding to cover separation near CFRP end. The load carrying capability of the beams failed by IC debonding is higher than that of the beams failed by cover separation near CFRP end. In addition, increasing shear span ratio can improve CFRP utilization;

- for the beams failed by IC debonding, more CFRP can provide the higher load carrying capacity and flexural stiffness, but it is not the case for the beams failed by cover separation near CFRP end. However, the increase of CFRP thickness would decrease the ductility of the strengthened beams.

Acknowledgments: cThe authors gratefully acknowledge the financial support provided by the National Natural Science Foundation (Project Nos. 51208117 ˙11372076), and Science and Technology Planning Project of Guangdong Province (2011B010400024).

References

1. XIE JH, HU RL. Experimental study on rehabilitation of corrosion-damaged reinforced concrete beams with carbon fiber reinforced polymer. Construction and Building Materials, 2013, 38: 178-188.
2. GUO YC, LI LJ, CHEN GM, HUANG PY. Influence of hollow imperfections in adhesive on the interfacial bond behaviors of FRP-plated RC beams. Construction and Building Materials, 2012, 30: 597-606.
3. XIE JH, HUANG PY, GUO YC. Fatigue behavior of reinforced concrete beams strengthened with prestressed fiber reinforced polymer. Construction and Building Materials, 2012, 27: 149-158.
4. NORRIS T, SAADATMANESH H, MOHAMMAD RE. Shear and flexural strengthening of R/C beams with carbon fiber sheets. Journal of Structural Engineering, 1997, 123 (7): 903–911.
5. CHAJES MJ, THOMSON TA, JANUSZKA TF, FIN W. Flexural strengthening of concrete beams using externally bonded composite materials. Construction and Building Materials, 1994, 8 (3): 191-201.
6. RAHIMI H, HUTCHINSON A. Concrete beams strengthened with externally bonded FRP plates. Journal of Composites for Construction, 2001, 5:44–56.
7. LI LJ, GUO YC LIU F. An experimental and numerical study of the effect of thickness and length of CFRP on performance of repaired reinforced concrete beams. Construction and Building Materials. 2006, 20(10): 901-909.
8. WANG WW, LI G. Experimental study and analysis of RC beams strengthened with CFRP laminates under sustaining load International Journal of Solids and Structures, 2006, 43: 1372-1387.
9. SHIN YS, LEE C. Flexural behavior of reinforced concrete beams strengthened with carbon fiber-reinforced polymer laminates at different levels of sustaining load. ACI Structural Journal, 2003, 100 (2): 231-240.
10. KIM HS, SHIN YS. Flexural behavior of reinforced concrete beams retrofitted with hybrid fiber reinforced polymers under sustaining loads. Composite Structures, 2011, 93: 802-811.
11. ARDUINI M, NANNI A. Behavior of Precracked RC beams strengthened with carbon FRP Sheets. Journal of Composites for Construction 1997, 1(2): 63-70.
12.SHAHAWY M, CHAALLAL O, THOMAS EB, ADNAN E. Flexural strengthening with carbon fiber-reinforced polymer composites of preload full-scale girders. ACI Structural Journal, 2001, 98 (5): 735-743.
13. BONACCI JF, MAALEJ M. Externally bonded fiber-reinforced polymer for rehabilitation of corrosion damaged concrete beams. ACI Structural Journal, 2000, 97 (5): 703-711.
14. FAYYADH MM, RAZAK H ABDUL. Assessment of effectiveness of CFRP repaired RC beams under different damage levels based on flexural stiffness. Construction and Building Materials, 2012, 37: 125-134.

Manuscript received: 28.04.2012