Experimental Study of Reinforced Concrete Beams Strengthened with CFRP

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Abstract. To test the strengthening effect of CFRP sheets on reinforced concrete (RC) beams, an experimental study was performed on five RC beams to analyze the influence of the amount of CFRP sheets and the sustained load of RC beams on the strengthening effect. The results showed that CFRP sheets could significantly improve the bending bearing capacity of the beams. However, there was no linear relationship between the amount of CFRP sheets and the strengthening effect, and the load on the beams had a great impact on the rigidity of the beams in the yield stage.

Keywords: Carbon Fiber Reinforced Polymer (Cfrp) · Strengthening · Reinforced-concrete beam · Bending test

1 Introduction

With the development of China's construction industry, the technology of strengthening concrete with CFRP sheets has been widely used in China's structures such as bridges and buildings due to the light weight, high strength, corrosion resistance, easy application and other characteristic of CFRP sheets [1]. Scholars at home and abroad have carried out a number of experimental studies and theoretical analyses on bending resistance of reinforced concrete (RC) beams strengthened with CFRP sheets [2–4], most of which are focused on the intact beams. However, the structures that need to be strengthened in the actual engineering are those of the existing engineering with insufficient bearing capacity and other conditions, so an analysis on the strengthening of RC beams under secondary load is necessary. At present, some achievements have been made in this field [5, 6]. In this study, an experimental analysis will be carried out on five beams on the basis of previous studies to compare the influence law of the amount of CFRP sheets and the sustained load state of RC beams on the failure characteristics of RC beams, concrete strain, rigidity of beams and ultimate bearing capacity.

2 Experimental Design

2.1 Specimen Design and Fabrication

According to the Code for Design of Concrete Structures (GB 50010-2010), five beams of the same size (the sectional size was 120 mm × 250 mm, and the length was 2500 mm)

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were designed and fabricated, as shown in Fig. 1. The strength grade of concrete of the test beams was designed to be C20, the tensile main reinforcement was HRB335, the erection reinforcement was HPB300, the stirrup was HPB300, and the reinforcement ratio was 1.52%. The tensile strength of CFRP sheets was 3550 MPa, the elasticity modulus was 235 GPa, and the thickness was 0.111 mm. Parameters such as the amount of carbon fiber and the sustained load point of each specimen are shown in Table 1.

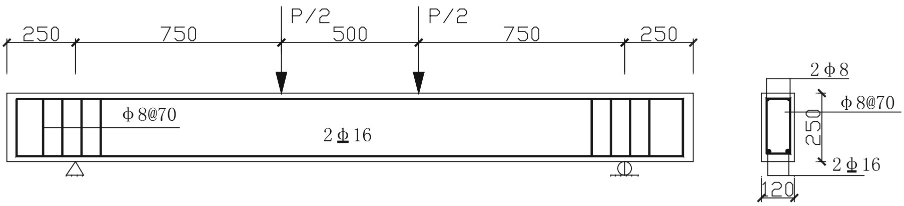

Fig. 1. Diagram of test beam reinforcement

Table 1. Specimen parameters

Specimen No	Ratio of longitudinal reinforcement	Amount of CFRP (Sheets)	Sustained load point	Remark
Beam1	1.52%	0	–	Not strengthened
Beam2	1.52%	1	–	Intact beam strengthened
Beam3	1.52%	2	–	Intact beam strengthened
Beam4	1.52%	1	$0.6P_y$	–
Beam5	1.52%	2	$0.6P_y$	–

2.2 Loading Scheme

The test beam was in the form of simply supported beam, with the test length of 2 000 mm and the length of simple bending segment of 500 mm. The loading diagram is shown in Fig. 1. Hydraulic jack was used for opposite side loading, and the experiment was carried out according to the Standard for Test Method of Concrete Structures [7]; when the load applied was close to the characteristic point load (such as the cracking point of concrete and the yield point of reinforcement), the loading level was reduced to accurately control the characteristic points; after yield of reinforcement, the loading was controlled by deflection until the specimen was destroyed. To keep the load on the beam unchanged when pasting the CFRP, the hydraulic jack was used for self-locking.

The surface of the tensile side of the beam was polished until the coarse aggregate was exposed, and the surface of the polished specimen should be flat; the dust was removed and the surface was washed with acetone. The surface was step-loaded to the pre-defined load grade according to the loading history in Table 1 and remained under this load (for ease of the following analysis, this point was referred to as the "sustained load point"), and then the CFRP was pasted.

3 Experimental Results and Analysis

The failure process of strengthened beam mainly had the following characteristics: the longitudinal bar yielded first, then the CFRP sheets peeled off the concrete in the simple bending segment or the bending-shear zone below the loading point, and finally the concrete in the compression zone was crushed; there were obvious elastic stage, stage of working with cracks and stage of yield of reinforcement during the destruction; there was no failure of over-reinforced beam that the CFRP sheets at the end peeled off the surface of concrete or the concrete in the compression zone was crushed first.

The load, deflection, rigidity and failure modes of the five specimens in each loading stage are shown in Table 2.

Table 2. Main experimental results

Specimens	Load (kN)			Deflection (mm)			Rigidity (N/mm, $\times 10^4$)			Failure modes
	P_{cr}	P_y	P_u	$_{cr}$	$_{y}$	$_{u}$	B_{cr}	B_y	B_u	
Beam1	10.0	65.2	68.7	1.0	7.6	17.2	0.971	0.840	0.037	Bending failure, concrete compression failure
Beam2	10.1	73.0	82.4	0.8	7.9	21.0	1.217	0.887	0.072	Protective layer in the bending segment peeled off
Beam3	9.1	71.6	85.1	1.0	8.6	18.8	0.910	0.819	0.133	Protective layer in the bending segment peeled off, concrete compression failure
Beam4	12.1	80.1	92.1	0.7	7.3	23.7	1.862	1.026	0.073	CFRP 30% tensile failure, concrete compression failure
Beam5	12.6	81.2	96.1	0.8	7.4	17.2	1.658	1.032	0.153	Protective layer in the bending segment peeled off, concrete compression failure

3.1 Characteristic Load Analysis

3.1.1 Cracking Load

The experimental data showed that there was no effect on the cracking load of beams strengthened with CFRP sheets. The cracking loads of Beam1, Beam2 and Beam3 without sustained initial load were basically the same, and the cracking load of RC beams did not change with or without CFRP. The reason is that the tension of the concrete at the bottom of the beam is mainly borne by the concrete in the tensile zone at the bottom of the beam, and when the tensile stress of the concrete in the tensile zone exceeds the tensile strength, the concrete is cracked. Due to the small load at the beginning of loading, the pasted on the tensile surface has not played the role of reinforcement and strengthening.

3.1.2 Yield Load and Ultimate Load

When the concrete was cracked and stopped working, the tension was borne by tensile reinforcement and CFRP together. As the load gradually increased, the original tension on the concrete at the bottom of the beam was borne by the CFRP sheets pasted at the bottom of the beam, which reduced the stress borne by the reinforcement and delayed the yield of reinforcement, thus improving the yield load of the beam to a certain extent. Comparison of the experimental results showed that the yield load was improved by 17% with one CFRP sheet and 18% with two CFRP sheets.

After yield of longitudinal reinforcement, the high strength and high modulus of CFRP were put to good use with the further increase of the load, and the ultimate bearing capacity of the beam strengthened with CFRP sheets was greatly improved, of which it was improved by 27% with one sheet and 32% with two sheets. The experimental results also showed that with the increase of the amount of the CFRP, the resistance to bending was improved, although it did not increase linearly.

3.2 Deflection and Rigidity Analysis

Analysis on the data in Table 2 showed that the deflection of Beam3 and Beam5 pasted with two CFRP sheets was lower than that of Beam2 and Beam4 pasted with one CFRP sheet under the ultimate load, suggesting that the amount of CFRP sheets had great impact on the deflection of the beams. Meanwhile, the amount of CFRP sheets could significantly improve the rigidity of the beams under the ultimate load, of which the rigidity of Beam2 and Beam4 pasted with one CFRP sheet was nearly twice that of Beam1 that was not strengthened under the ultimate load, and the rigidity of Beam3 and Beam5 pasted with two CFRP sheets was nearly twice that of Beam2 and Beam4 pasted with one CFRP sheet under the ultimate load. This suggested that CFRP sheets could effectively improve the rigidity of the beams under the ultimate load, and the degree of the improvement was linearly related to the amount of the CFRP sheets.

4 Conclusion

In this experiment, one control beam and four test beams were used to analyze the impact of the amount of CFRP sheets and the sustained load points on the strengthening effect of CFRP sheets on RC beams, and the following conclusions were drawn. 1) The bearing capacity of the beams strengthened with CFRP sheets was greatly improved. However, the improvement rate was not linearly related to the amount of the CFRP. 2) The ultimate state of the RC beams strengthened with CFRP sheets was delayed under a certain load (such as 0.6 P_y), and the ultimate bearing capacity was also improved with the increase of the amount of CFRP. 3) The rigidity of the RC beams strengthened with CFRP was significantly improved, compared with the ordinary RC beams, and the CFRP sheets could improve the rigidity and control the deflection of the components mainly resistant to bending. With the increase of the amount of the CFRP, the rigidity of the beams also increased. 4) The load of the strengthened beams had a great impact on the rigidity of the beams in the yield stage.

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