Flexural Performance of BFRP Bar Reinforced High-Strength Concrete Beam

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Abstract. Although fiber reinforced polymer (FRP) can improve the bearing capacity of concrete structures, it always shows the brittle failure. This paper used high strength concrete RPC combined with BFRP bar to produce a new type of beam. The results of a four-point bending test shown that: the RPC-BFRP beam presented a plastic failure model as its load-deflection curve was similar to the steel bar RC beam. Otherwise, the BFRP bar reinforced normal concrete beam gave out a brittle failure as its load-deflection curve showed a bilinear model.Due to the higher utilization efficiency of BFRP bars as well as the high strength of RPC, the cracking load and the ultimate load of RPC beams were significantly higher than that of normal concrete beams. The new type RPC-BFRP beam showed a positive effect on both the flexibility and bearing capacity.

Keywords: BFRP bar · Reactive Powder Concrete (RPC) · RC beam · Plastic failure model · Flexural properties

1 Introduction

The reinforced concrete structure is the most commonly used form of building construction in the field of civil engineering in the world today. However, due to the corrosion of chloride ions in seawater and sea wind, the durability of reinforced concrete structure in coastal area is insufficient [1–3]. In recent years, in order to improve the durability of building structures in coastal areas, some scholars have proposed using FRP (Fiber Reinforced Polymer) bars to replace steel bars to solve the problem of steel bar corrosion [4–7].

FRP is a high-strength and high-performance new material [8–12], which has a wide range of applications in the field of civil engineering. It is attributed to the advantages of light weight and high strength, good corrosion resistance, strong designability, and good dielectric properties. With FRP composite being widely studied and applied in the world, it is found that FRP reinforcement has the advantages of good fatigue performance, small

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stress relaxation, good corrosion resistance, electromagnetic insulation and so on [13]. Therefore, the long-term comprehensive benefit of FRP composite used in structural engineering is better than that of steel reinforcement. Since FRP bars will not rust like steel bars, they can be directly mixed into sea water and sea sand concrete without any treatment. In this way, the rich natural sea sand and sea water resources can be directly used to reduce the dependence of construction projects on river sand and fresh water resources. So in recent years, many scholars have proposed to use basalt fiber reinforced polymer (BFRP) bar, carbon fiber reinforced polymer (CFRP) bar and glass fiber reinforced polymer (GFRP) bar instead of steel bars, which can fundamentally solve the problem of insufficient durability of concrete structures caused by corrosion of steel bars, and improve the bearing capacity of concrete structures with high strength of FRP [14–17].

Leung et al. [18] found that using GFRP Bars to replace a part of the tension bars will increase the flexural capacity of concrete beams with the increase of reinforcement ratio and concrete strength, and the increase of concrete strength significantly changes the failure mode of beams. Hasan et al. [19] studied and analysed the existing literature and data, and concluded that in the concrete beam strengthened with GFRP reinforcement, increasing the GFRP reinforcement ratio can reduce the maximum midspan deflection and crack width. Kalpana et al. [20] found that GFRP reinforced concrete beams constructed with high-strength concrete can provide better bearing capacity and smaller deflection compared with GFRP reinforced concrete beams constructed with ordinary strength concrete. Hua et al. [21] combined BFRP with sea water sand concrete to study its failure mode, bearing capacity, deflection and crack width. The reinforcement ratio, section height, steel bar diameter and type were taken as test parameters. The results showed that the flexural bearing capacity, crack width, and deflection of BFRP reinforced beams were much higher than those of reinforced beams. With the increase of reinforcement ratio, the tensile failure of BFRP reinforced beams became a balance failure and eventually becomes a compressive failure. BFRP bars with smaller diameter had better bond performance with concrete, and can reduce the width of cracks without affecting the bearing capacity and deflection. Ovitigala et al. [22] studied the service performance and ultimate load characteristics of BFRP reinforced beams with different BFRP reinforcement sizes and in the range of 1.43–10.7. They obtained that the ultimate bearing capacity of beams was directly related as. With the increase of the bending capacity and the deflection change rate of the beam decreased. The higher can reduce the deflection better than the increase of the ultimate strength of beam. The strain coordination equation of ACI440.1R-06 was conservative in predicting the ultimate bending strain and bending capacity of the BFRP reinforced beam.

Farid et al. [23] applied BFRP bars to fiber-reinforced concrete (FRC). After bending tests on 12 test beams, it is found that the ductility of BFRP reinforced concrete beams can be improved by adding fiber into the concrete, and the fiber in the concrete can effectively inhibit the expansion of crack width and depth. Zhu et al. [24] found that by incorporating steel fibers in the tensile zone of BFRP reinforcement beams, they can effectively overcome the large deflections and large crack widths of BFRP reinforcement beams. Still, the flexibility of beam reduced, so it is necessary to add steel fibers in the full depth of structures for the structures with high ductility requirements. Farid et al.

[25] carried out bending tests on ten beams, three of which were strengthened with steel bars as the control group, and seven of which were strengthened with BFRP bars. The results showed that the bearing capacity of all the beams strengthened with the BFRP bar was slightly higher than that of the beams strengthened with steel bars, but the load-deflection curve was linear and showed brittle failure when reaching the ultimate shear capacity.

Although the tensile strength of FRP bars is much higher than that of steel bars, FRP is a brittle material, and there is no significant yield stage in the process of fracture. The current research results show that although the strength of RC beams strengthened with FRP is higher than that of reinforced beams, the strength of FRP bars can not be fully developed, and brittle failure often occurs in RC beams strengthened with FRP bars [26]. In the service stage, the crack and deflection develop greatly, so FRP bars are still limited in engineering application.

In order to solve this problem, the high-strength RPC and BFRP reinforcement were combined in this experiment to make the strength of FRP reinforcement play an effective role. Reactive Powder Concrete (RPC) is a new type of ultra-high-performance material developed by the team of Pierre Richard's expert research team in France in the 1990s [27]. This kind of concrete is quite dense, has small internal original defects, and is not easy to generate stress concentration and other undesirable phenomena [28, 29], so it has very high compressive strength. It has been found that its strength can reach 200–800 Mpa [30], and its elastic modulus can reach 50 GPa. And RPC also has excellent shear, freeze and corrosion resistance [31, 32]. Some studies found that RPC with a proper amount of steel fibers has a high ultimate compressive strain and significantly improves the flexural resistance and energy absorption capacity [26, 28]. By combining RPC with FRP, the compressive strain capacity of concrete can be improved, so as to delay the compression failure of concrete, and FRP bars can make a greater contribution to the bearing capacity of concrete, which can give full play to their excellent properties and solve the shortcomings of brittle failure of FRP bars. Therefore, the flexural behavior and ductility of RPC beams strengthened with BFRP bars are studied in this test. The change of bearing capacity, failure mode, deflection and deformation of RPC beams reinforced with BFRP are analysed and compared with those of normal concrete beams reinforced with BFRP bars and steel bars.

2 Methodology

2.1 Materials

BFRP bar and steel bar of 8mm were used as reinforced bar, all the properties were provided by the manufacturer and were listed in Table 1.

Reactive powder concrete (RPC) and Geoolymer concrete (GPC) were used, and the mixture were shown in Table 2 and Table 3. Three standard cubes with a side length of 150 mm were made and cured in the same environment as the test beam. After 28 days, the compressive strength of activated powder sea sand concrete and inorganic polymer sea sand concrete were 90.47 MPa and 36.55 MPa, respectively.

Table 1. Mechanical properties of reinforcement.

Material	Yield strength f_y, (MPa)	Ultimate strength f_u, (MPa)	Elastic modulus *E*, (GPa)	Elongation (%)
Steel	415	625	200	29
BFRP	–	970	49	2.8

Table 2. Mix proportions of RPC.

Cementitious materials (kg/m$^{3)}$		Sea sand (kg/m$^{3)}$	Steel fiber (kg/m$^{3)}$	Seawater (kg/m$^{3)}$	Superplasticizer (kg/m$^{3)}$
Cement	Admixture				
24	6	55	5	4.9	0.72

Table 3. Mix ratio of geopolymer concreter(kg/m^3).

Geopolymer	Slag	Fly ash	Sea sand	Gravel	Sea water
265	71	106	654	1114	190

2.2 Specimen Preparation and Testing

The size of beam specimen was 100 mm*200 mm*1500 mm, and the concrete cover was 20 mm. A schematic picture of the specimen is shown in Fig. 1 and 8 beams of 3 types were catalogiezd in Table 5. All the beams were subjected to a four-point flexural testing while keeping the support 100 mm from the boundary. The loading span was 1300 mm, and the constant moment zone and shear span were the same sizes (433 mm). The beams were instrumented with two LVDTs in the testing region (pure bending region) to monitor the mid-span deflection. Two strain gauges were mounted at the top surface of the beam to record the compressive strain of concrete. The load was applied using the SDS500 electrohydraulic servo static and dynamic universal testing machine The load was applied at a rate of 1 kN/min until cracking was observed (cracking load), and subsequently, the rate was increased to 2 kN/min until beam failure. A TDS530 static strain data collector was used to measure strain (Table 4).

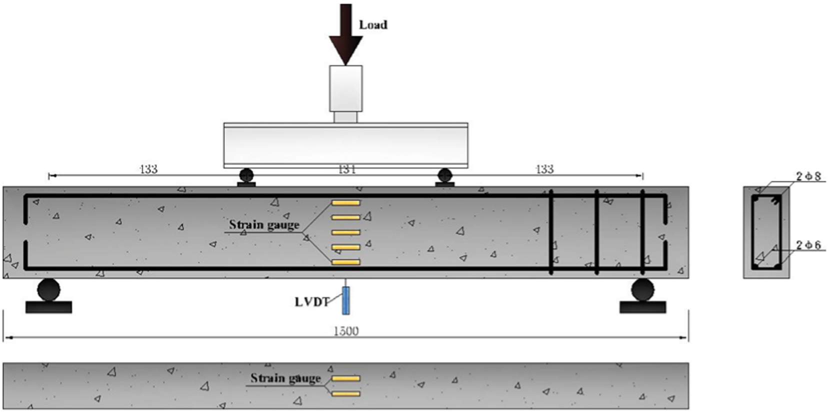


Fig. 1. Testing scheme of the RC beam with cross-sectional details (all units in mm).

Table 4. Summary of the specimens.

Reinforcement		Type of concrete	Number of specimens	Specimen no.
Type	Dia. (mm)			
Steel	8	GPC	3	BSI-8
BFRP	8	GPC	3	BBI-8
BFRP	8	RPC	2	BBR-8

Note: The first character, “B”, represents the specimen beam; the second character, “S” or “B”, represents the reinforcement type for steel and BFRP; the third character, “I” or “R”, represents the concrete type for GPC and RPC; the fourth character, “8”, is the rebar diameter

3 Experimental Results and Discussion

3.1 Flexural Stength

All the beams were subjected to a four-point bending test. The load value is shown in Table 5.

Table 5. Load value of beams.

Specimen	Cracking load (kN)	Ultimate load (kN)
BSI-8	16	44.5
BBI-8	12	54.1
BBR-8	32	84.8

The cracking load and ultimate load of the BBR-8 was significantly higher than the others. The cracking load of BBR-8 was 100% and 167% higher than that of BSI-8 and

BBI-8, and the ultimate load was 91% and 57% higher, respectively. The RPC-BFRP beam showed a better cracking resistance and bearing capacity. The tensile elastic modulus of BFRP is smaller than that of steel bar, which often cause to the early occurrence of cracks in concrete beams. However, because the tensile strength of RPC concrete is higher than that normal concrete, the cracking load of RPC beams is greatly increased. In addition, because of the higher compressive strength of RPC, the which has the ultimate load of the BBR-8 was greatly improved.

3.2 Load-Deflection

During loading, the load value and deflection of beams were monitored and were shown in Fig. 2.

The load-deflection curve of the steel bar reinforced beam (BSI-8) shown a typical trilinear model. However, the load-deflection curve of the BFRP bar reinforced normal concrete beam shown a bilinear model which defined a brittle failure. But for BFRP bar reinforced RPC beam, the load-deflection curve presented a trilinear model, which contained a yield section and indicated a plastic failure. The new type of BFRP bar reinforced RPC beam gave out a excellent performance: good ductility, high bearing capacity and plastic failure model.

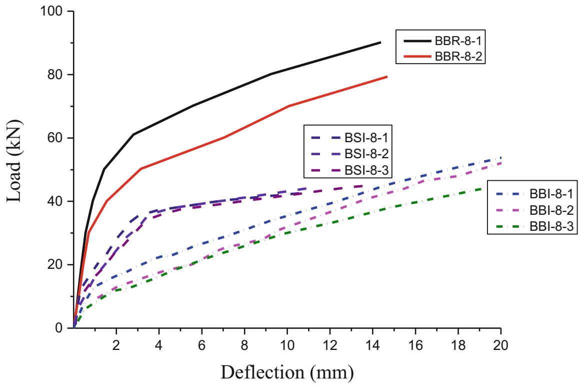
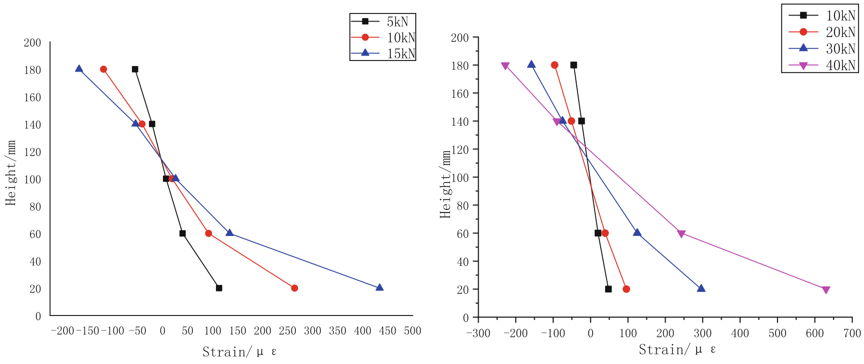


Fig. 2. The load-deflection curves of beams

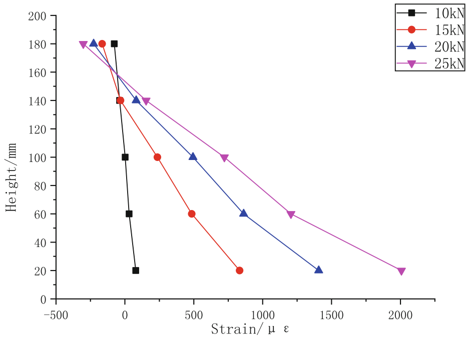
3.3 Cross-Section Strain

Selected the mid-span concrete section strain for cross-section strain analysis. The cross-section strain distribution along section height was shown in Fig. 3.

Under different loads,the distribution of the section strain along the height of the beam passes through the same point. The cross-section strain of the beams changed approximately linearly along the height of the cross-section in each level of load. Therefore, it can be considered that all beams conformed to the plane section assumption. The neutral axis of beams reinforced with BFRP bar was lower than steel bar reinforced beam. This means larger compression zone area and higher bearing capacity. Under the same load, the strain increment of the BBR-8 was the smallest and the stress was more average.This benefits from the restraint effect of steel fibers in RPC, which helps the BFRP bar to be more fully utilized. The strain development of cross-section concrete also benefited from the restraint of steel fiber in RPC. Before cracking, the strain of BBR-8 increased the slowest with the increase of load and had the highest cracking load. After cracking, the tensile force in the BBI-8 was all beared by BFRP bar. Compared with steel bar, the elastic modulus of BFRP bar was smaller,so the concrete strain of BBI-8 growth had a sudden change.In BBR-8, due to the steel fiber and BFRP bar shared the tensile force, the concrete strain can grow smoothly after the cracks formed.



(3a)BBI-8 (3b)BBR-8



(3c)BSI-8

Fig. 3. Cross-section strain distribution along section height.

3.4 Efficiency of BFRP Reinforced Bar

Following the FRP reinforced concrete structures design standards, such as the ACI 440.1R of United States, CSA S806 and of Canada, and GB50608–2010 of China, the efficiency of BFRP bar was calculated and listed in Table 6. Under the same limit of deflection, the ultimate bending capacity of BBR-8 was up to 70%, but the that of BBI-8 was only around 40%. The flexural performance and safety threshold of BBR-8 are both better than that of the others.

Table 6. Efficiency of BFRP reinforced bar.

Specimen number	Ultimate load (kN)	Experimental value (mm)	$D = {}^{\phi_u}/_{\phi_k}$	Limit load / Ultimate load		
		Service load ($0.3M_u$)		ACI 440.1R-15	CSA S806–12	GB 50608–10
BBI-8	51.03	3.06	6.77	0.51	0.43	0.49
BBR-8	84.84	0.50	29.40	0.80	0.74	0.77

Note: D is deformation safety reserve index; ϕ_u is the deflection at failure; ϕ_k is the deflection in service

4 Conclusions

A four-point bending test was adopted in the BFRP reinforced RPC beams, BFRP reinforced normal concrete beam and the steel bar reinforced normal concrete beam.

1. The cracking load and ultimate load of the BBR-8 was significantly higher than the others. The cracking load of BBR-8 was 100% and 167% higher than that of BSI-8 and BBI-8, and the ultimate load was 91% and 57% higher, respectively.
2. The load-deflection curve of BBR-8 presented a typical trilinear model which contained a yield section and indicated a plastic failure. However, the BBI-8 shown a bilinear model which defined a brittle failure.
3. The cross-section strain analysis shown that BSI-8, BBI-8 and BBR-8 both conformed to the plane section assumption.
4. The flexural performance and safety threshold of BBR-8 are both better than that of the others, and the efficiency of the BFRP bar was upto 70%.

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