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Flexural behavior of concrete beams reinforced with CFRP prestressed prisms

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Abstract. An experimental investigation on the behaviour of concrete beams reinforced with various reinforcement, including ordinary steel bars, CFRP bars and CFRP prestressed concrete prisms(PCP). The main variable in the test program was the level of prestress and the cross section of PCP.The modes of failure and the crack width were observed. The results of load-deflection and load-crack width characteristics were discussed. The results showed that the CFRP prestressed concrete prisms as flexural reinforcement of concrete beams could limit deflection and crack width under service load and PCP can overcome the serviceability problems associated with the low elastic modulus/strength ratio of CFRP.

Keywords: flexural behavior; beams; CFRP; deflection; crack width

1. Introduction

Today, use of fiber reinforced polymers (FRP) as reinforcement for concrete structures is gaining more acceptance among researchers and engineer. Their unique material properties such as high tensile strength, light weight, and high corrosion resistance, have encouraged researchers and engi-neers to consider these materials as potential replacement for steel as reinforcement especially in harsh environments.

For the past few years, several investigations were conducted to study the mechanical performance of FRP reinforced concrete beams. Kara *et al.* (2015) presented a numerical method for estimating the curvature, deflection and moment capacity of hybrid FRP/steel reinforced concrete beams. Tomlinson *et al.* (2015) evaluated the flexural and shear performances of concrete beams reinforcedwith basalt fiber-reinforced polymer (BFRP) rebar and stirrups. Zhang *et al.* (2014) studied the flexural defections of concrete beam reinforced with basalt FRP bars and proposed a modified equation of the flexural rigidity to calculate the deflection of the FRP-RC beams Wang *et al.* (2013) studied the long-term flexural behaviors of a hybrid system consisted of

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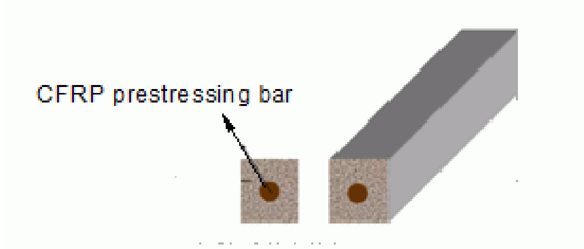


Fig. 1 Typical CFRP prestressed concrete prism(PCP)

continuous fiber-reinforced-polymer (FRP) rebar and fiber-reinforced-concrete (FRC). Kara *et al.* (2012) proposed numerical technique for estimating the curvature, deflection and moment capacity of FRP reinforced concrete beams. Robert *et al.* (2012) comparative studied among various code equations was conducted to predict the shear strength of FRP reinforced concrete beams. Wu *et al.* (2010, 2012) studied the behaviors of steel/FRP composite bar reinforced concrete beams.Issa and Metwally (2011) studied the influence of fibers on flexural behavior and ductility of concrete beams reinforced with GFRP bars. Kassem and Farghaly (2011) found the dominant failure mode of FRP RC beam was concrete crushing instead of FRP rupture because of the linear elastic behavior and high strength of FRP. Mostafa *et al.* (2011) investigated the behavior of continuous concrete beams reinforced with carbon and glass FRP bars and provided design guidelines to predict the failure load and failure location. Lu *et al.* (2015) examined the effect of carbon fiber reinforced polymer (CFRP) on the shear strengths of deep beams with web openings. Panjehpour *et al.* (2014) investigated the effect of CFRP-strengthening on the energy absorption of RC deep beams.

However, serviceability of FRP reinforced concrete structures has always been a major concern since most of these materials have a relatively low axial stiffness (EA) compared to steel. Due to this fact, the deflection of FRP reinforced flexural members is larger than that of conventionally steel reinforced members. Crack widths are also wider for FRP reinforced concrete in comparison with similarly steel reinforced members. In addition, FRP materials behave elastically up to failure which causes lack of ductility in FRP reinforced flexural elements at ultimate unless the section is over-reinforced well above the balanced as an alternative reinforcement for concrete are expected. Steel prestressed concrete prisms have been used over the past 40 years for crack control and reinforcement in simply supported and continuous beams (Hanson 1969 and Bishara *et al*. 1971). Recent works have been conducted on steel PCP reinforced simply supported high strength concrete rectangular beams (Chen and Nawy 1994) and continuous T beams (Nawy and Chen 1998) whereas carbon fiber reinforced polymer (CFRP) prestressed prisms were used as reinforcement in simply supported beams (Svecova and Razaqpiir 2000). Glass fibre reinforced polymer (GFRP) prestressed prisms were used as straps in steel free bridge decks (Banthia *et al*. 2003). However, the behavior of CFRP Prestressed Prisms reinforced concrete beams has been few studied to date. In this study, the flexural behavior of several CFRP Prestressed Prisms reinforced concrete beams is tested.

2. Experimental programme

Table 1 Reinforcement details of all tested beams

Beam number	Tension reinforcement	Prestress (kN)	Compressive reinforcement	Stirrup	
				Mid-span	Shear span
BL	1 Φ 16 + 2 Φ 12	——			
HL	1ϕ7CFRP + 2 Φ 12	35			
WL	1 PCPs + 2 Φ 12	0			
PL1	1 PCPs + 2 Φ 12	35	2Φ8	φ8@200	φ8@100
PL2	1 PCPs + 2 Φ 12	43			
PL3	1 PCPs + 2 Φ 12	35			
PL4	1 PCPs + 2 Φ 12	35			

2.1 CFRP prestressed concrete prisms

Fig. 1 illustrates a typical geometry of a prestressed concrete prism(PCP) that was used in this experimental investigation. The prisms were 40×40 mm in cross section and 2.2 m long, expect for the prisms used in one beam, which had a 60×40 mm in cross section. High- strength concrete with a compressive strength of 154 Mpa and a tensile strength of 17.4 Mpa was used to cast the prisms. Each prisms was concentrically prestressed by an 7 mm diameter single CFRP bar. According to the manufacturer, the ultimate tensile strength of this bar was 2200 Mpa withmodulus of elasticity of 155 Gpa. The jacking stresses varied from 880Mpa to 1320 Mpa, which are equal to 0.40 to 0.60, respectively, of the guaranteed tensile strength.

2.2 Test beams

A total of seven concrete beams were tested and the reinforcement details for each beam are listed in Table 1. Fig. 2 shows the typical dimensions, and loading arrangement of the beams. All beams had a equal clear spans of 2 m, a cross section of 160×250 mm,a diameter of 8 mm of steel bars as stirrups and as compression reinforcement. The beams were loaded in four-points bending over a shear span of 700 mm. The difference among the beams was their tensile reinforcement. All beams were cast with normal strength concrete ordered from a local mixing plant. The compressive strength of concrete of all beams was 48.8 Mpa.

2.3 Instrumentation and test setup

Electrical resistance strain gauges were used to measure the strain in the tension and compression reinforcement. Strain gauges were also used to monitor strain in concrete. Beam deflection was measured using linear variable displacement transducers (LVDTs) placed along the beam. All the beams were tested in four-points bending and simply supported. The load was applied by a servo-hydraulic testing machine. The load from the actuator was converted to two-point loads at 0.7 m from the center support using a steel spreader beam. The load was applied monotonically until failure. The load was applied by using a displacement rate of 0.01 mm/s, and the automatic data acquisition system recorded data every 10 seconds. Fig. 3 shows the test setup for the beams.

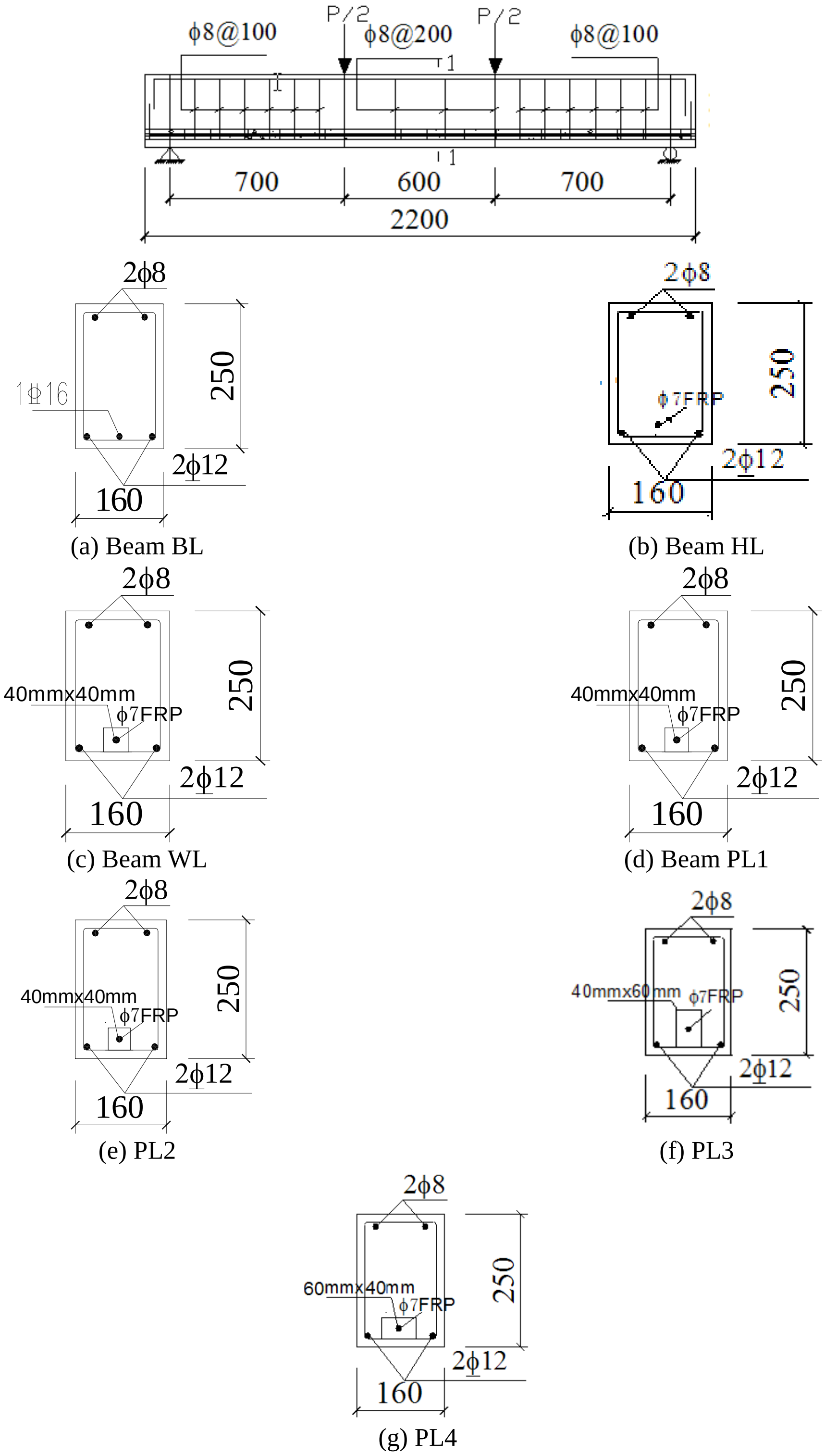
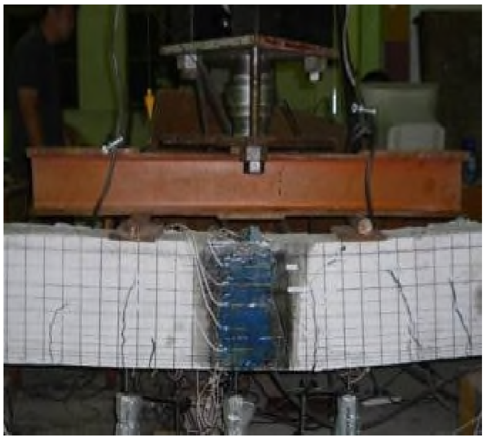


Fig. 2 Typical dimensions and geometry of tested beams

Fig. 3 Test setup

(a) Beam BL



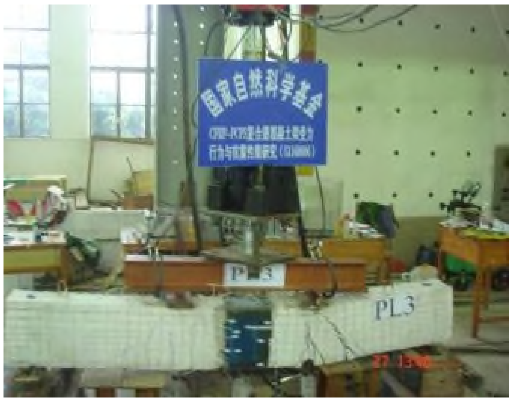
(b) Beam HL

(c) Beam WL

(d) Beam PL1

Fig. 4 Failure modes of beams

(e) PL2



(f) PL3

(g) PL4

Fig. 4 Continued

3. Experimental results

3.1 Failure pattern

Fig. 4 shows the failure modes of beams. There are three failure pattern observed in the test: (a) concrete crushing after steel reinforcement yielded. (Beam BL, Fig. 4(a)); (b) compression failure of concrete beams without rupture of CFRP bar ((Beam HL (Fig. 4(b)), Beam WL (Fig. 4(c)), Beam PL1 (Fig. 4(d)), Beam PL2 (Fig. 4(e)), Beam PL3 (Fig. 4(f))); (c) compression failure of concrete beams with rupture of CFRP bar (Beam PL4 (Fig. 4(g))).

For beam BL, the first flexural crack which width was 0.11mm appears in the mid-span when the load was 36 kN. The flexural-shear cracks appeared in the left shear span and the right shear span when the load was 76 kN. In all loading process, a total of eight cracks appeared in the pure bending section, which spacing and width was bigger. For beam HL and beam WL, flexural cracks initially appeared at the pure bending region. The flexural-shear cracks then appeared as the load

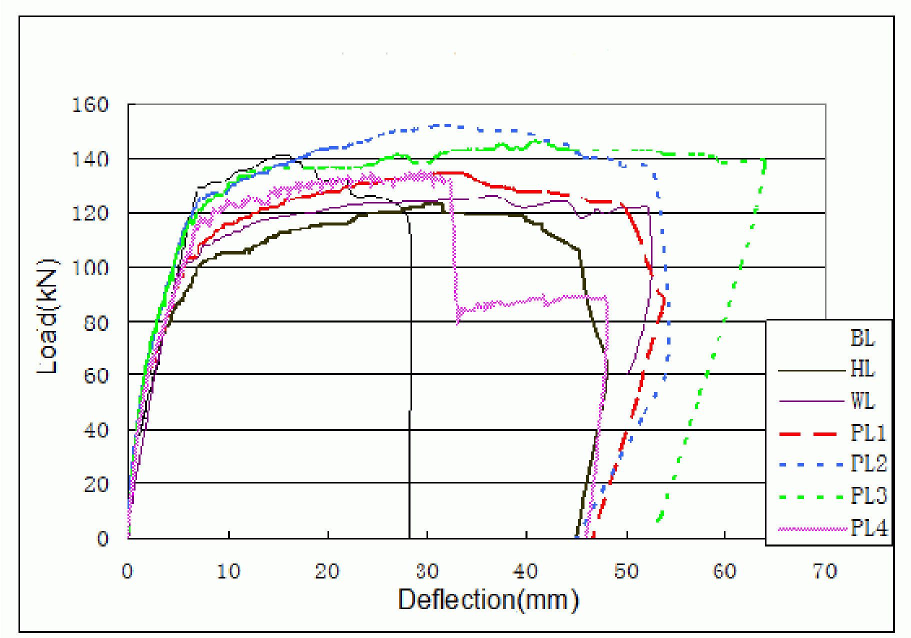


Fig. 5 Load-deflection curves of the tested beams

increasing, and compression failure eventually occurred to both beam HL and beam WL when concrete crushed in the compression face of the beam. For Beams PL1, PL2, PL3 and PL4, the crack patterns were similar, which mostly were flexural crack together with small flexural-shear cracks. The total cracks in beam PL4 was the most than that other beams, and the sound of gradual rupture of the CFRP could be heard.

3.2 Load-deflection curve

Fig. 5 shows the typical experimental load deflection curves of all beams under the load point. The beam BL cracked at 36 kN, and its maximum deflection at mid-span was 0.76 mm. When the steel started to yield at around 131 kN, the mid-span deflection nearly reached to 7.1 mm. The beam failed at 120 kN, and its maximum deflection at mid-span reached 28 mm, four times the amount at yield. For beam HL, it cracked at 41.8 kN, and the deflection at ultimate load of 108 kN was 45 mm. Due to extensive cracking was evident at 75% of the ultimate load, it was difficult to anticipate the actual failure. For beam WL, it cracked at 40 kN, which was consistent with beams ST and beam L. Throughout the loading process, the beams behaved very similarly to beam L and the load-deflection curves had a noticeable flattening can be observed . The beam failed at 120 kN, and then its maximum deflection increased to 48 mm. For beam series PCP, the load deflection curves show a bi-linear response with no change in stiffness after prism cracking. And the cracking of the beam did not noticeably affect the load deflection curve, because of the prestress in the reinforcing prisms. A comparison of the deflections of beams BL, HL, WL and series PCP revealed that the beams reinforced with prestressed concrete prisms have less deflection, before cracking of the prisms, the deflection was even less than the steel reinforced beam' deflection. The trend of decreasing beam deflection with increasing prestressing in the prisms was evident.

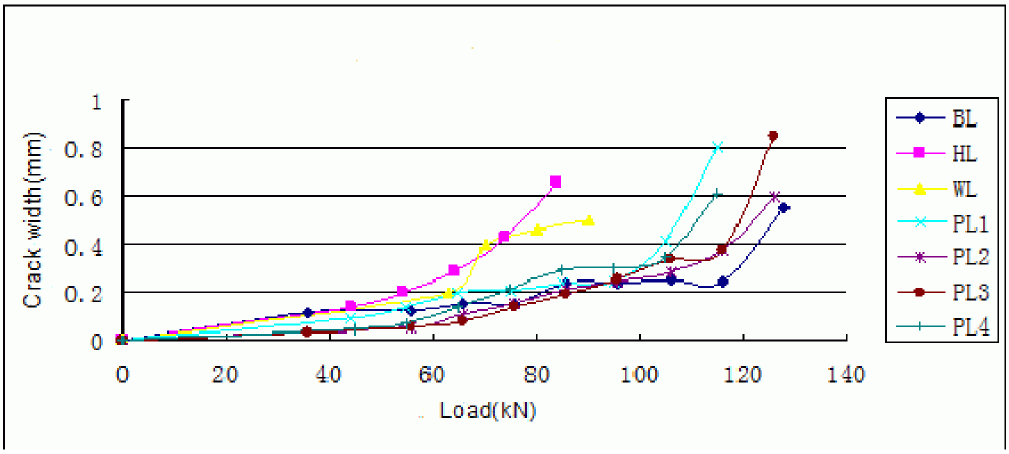


Fig. 6 Load-crack width curves of the tested beams

3.3 Ultimate load capacity

The load-deflection curves of the tested beams in Fig. 5 show an increase in ultimate load capacity with increased level of prestress, but the increase is not linearly proportional. Although all of the beams, except Beam BL, have the same amount of CFRP reinforcement, the beam whose prisms had the higher prestress had 8%~16% higher capacity than the beam without prestressed prisms. And the cross section of PCP is greater, the ultimate load capacity of beam series PCP is higher.

3.4 Crack

Fig. 6 shows the load-crack width curves. It seemed that the crack width varied depending on the type of reinforcement. A comparison of the crack of beams BL and series PCP reveals that the crack development of the beams reinforced with prestressed concrete prisms was slower. A comparison of the deflections of beams HL and series PCP revealed that the beams reinforced with prestressed concrete prisms have less crack width. This showed that prestressed concrete prisms played a good crack resistance in beams. After the crack pattern stabilizes, the load -crack width curve remained almost linear. Cracks appeared under higher load in prisms with higher prestress level but they widen at a faster rate compared to the prisms with lower prestress.

3.5 Ductility

The ductility of concrete beams is defined as the deformation capacity from the yield point to the peak load point(or the 85% of the peak load),and the displacement ductility coefficient could be defined as $u = \frac{\Delta_u}{\Delta_y}$,where Δ_u stands for the peak displacement, Δ_y stands for the yield displacement. The displacement ductility coefficients were shown in Table 2. It is shown that compared with the ordinary concrete beam, the beams reinforced with prestressed concrete prisms have higher ductility, the ductility coefficient of Beam PL3 is twice than Beam BL. And the

Table 2 Deflection and ductility coefficient of the beams

Beam		BL	HL	PL1	PL2	PL3	PL4
Crack	Δ_{cr}(mm)	0.76	1.04	1.12	1.1	1.11	1.11
Yield	Δ_{y}(mm)	7.1	7.38	7.51	7.22	7.81	7.2
Peak	Δ_{u}(mm)	28	45	50.6	49	62	36
Ductility coefficient μ		3.9	6.1	6.74	6.8	7.9	5

displacement ductility coefficient of beam HL is higher than beam BL, it shown the beams reinforced with prestressed CFRP bar has good ductility. The displacement ductility coefficient of Beams PL1 ,PL2 and PL3 are higher than Beam HL, shown that the beams reinforced with prestressed concrete prisms' ductility performance was better than the beams reinforced with prestressed CFRP bar. With the increase of prestress, the ductility performance basically remains unchanged, and the prestress has little effect on the ductility of the beams reinforced with prestressed concrete prisms. In all the beams reinforced with prestressed concrete prisms, the ductility coefficient of beam PL3 is the tallest, it shown that section size of prestressed concrete prisms could significantly increased the ductility of the beams .

4. Conclusions

Based on the experimental results, the following conclusions can be drawn:

• The beams reinforced with prestressed concrete prisms have a better crack resistance compared to the beams reinforced with prestressed CFRP bar.

• The improvement in stiffness of prestressed concrete prisms results in an decreased in crack width. As the prestress increases, the changes in ultimate crack widths are relatively large.

• Increased level of prestress in the prism reduces deflections of the PCP reinforced beam. The deflection of beam reinforced with highly prestressed prisms is at service loads comparable to deflection of steel reinforced beam, and is four times smaller than the deflection of a similar FRP reinforced beam.

Acknowledgments

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