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Mechanical properties of concrete beams reinforced with CFRP prestressed prisms under reverse cyclic loading

Jiongfeng Liang[*1,2], Deng Yu[3], Jianbao Wang[2] and Pinghua Yi[2]

[1]*State Key Laboratory Breeding Base of Nuclear Resources and Environment, Fundamental Science on Radioactive Geology and Exploration Technology Laboratory, Nanchang, P.R. China*
[2]*Faculty of Civil&Architecture Engineering, East China Institute of Technology, Nanchang, P.R. China*
[3]*College of Civil and Architecture Engineering, Guangxi University of Science and Technology, Liuzhou, P.R. China*

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Abstract. This paper presents the results of cyclic loading tests on 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 seismic performance indexes including hysteretic loops, skeleton curve, ductility, energy dissipation capacity and stiffness degradation were analyzed. The results show that the CFRP prestressed concrete prisms as flexural reinforcement of concrete beams has good seismic performance. And the ductility and the energy dissipation capacity were good, the hysteresis loops were full and had large area.

Keywords: CFRP; prism; cyclic loading; beam; seismic performance

1. Introduction

Today, use of fibre reinforced polymer (FRP) materials has become a more common practice in construction. FRP materials have unique mechanical properties such as high tensile strength, light weight, corrosion resistance, and magnetic neutrality.

Over the last couple of decades, several investigations were conducted to study the flexural and shear performance of FRP reinforced concrete structures (Elgabbas *et al*. 2016, Ferrier *et al*. 2016, Adam *et al*. 2015, Pawłowsk and Szumigała 2015, Mahroug *et al*. 2014, Ashour and Kara 2014). There were a few researches about the performance of FRP reinforced concrete structures under cyclic loading.

Kesavan *et al*. (2013) studied the performance of reinforced concrete beam strengthened with CFRP under cyclic loading using Fiber Bragg Grating (FBG) array. Bae *et al*. (2013) investigated the shear performance of an RC beam strengthened in shear with externally bonded carbon fiber reinforced polymer (CFRP) strips, subjected to a cyclic loading for 2 million cycles at 1 Hz. The results showed that RC beams strengthened in shear with externally bonded CFRP could survive 2 million cycles of cyclic loading without failure. Furthermore, the residual shear strength of the FRP

∗Corresponding author, Ph.D., E-mail: jiongfeng108@126.com

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strengthened beam appeared to be greater, than the static shear strength of the unstrengthened control beam. This study's results also suggested that limiting the interfacial stress in CFRP strips to less than 1.5 MPa or 25% of its ultimate interfacial strength would increase fatigue life by avoiding debonding of CFRP strips. Saiedi *et al.* (2011) investigates the behavior of concrete beams prestressed with carbon fiber reinforced polymer (CFRP) rods under high-cycle fatigue at low temperature. It was shown that the bond between CFRP rods and concrete could be weakened because of cyclic loading, low temperature during loading, or high prestress level. The premature bond failureat 70 to 90% of the full flexural strength in subsequent monotonic loading. Also, stiffness and camber gradually decreased during cyclic loading. Yet, the mechanical performance of FRP reinforced concrete beams under reverse cyclic loading has rarely been reported. Sakar *et al.* (2014) evaluate experimentally and numerically the cyclic loading response of reinforced concrete (RC) beams strengthened in shear with Glass Fiber Reinforced Polymer (GFRP) rods using the near surf-ace mounted (NSM) technique. Youssf *et al*. (2016) investigated the possible use of crumb rubber concrete (CRC) for structural columns by evaluating the use of fibre reinforced polymer (FRP) confinement as a means of overcoming the material deficiencies (compressive strength). Selman *et al.* (2015) studied FRP-strengthened reinforced concrete beam under cyclic load by acoustic emission technique. Realfonzo *et al.* (2014) investigated the seismic performance of RC beam-column joints strengthened with FRP systems. Faustino and Chastre (2015) studied different external strengthening systems applied to rectangular reinforced concrete columns with rounded corners. Carneiro and Melo (2011) presented an analytical model to simulate the behavior of prestressed concrete girders strengthened with various carbon fiber-reinforced polymer systems and subjected to static and cyclic loading.

However, most FRP materials have relatively low modulus of elasticity compared to steel. Due to this low modulus and the relatively small cross sectional area of FRP bars, when FRP reinforced concrete flexural members crack, the neutral axis considerably shifts up in the section causing a significant decrease in flexural stiffness. This is accompanied by increased deflections and crack widths under service load condition. To eliminate these problems, use of FRP prestressed concrete prisms (PCP) as an alternative reinforcement for concrete had been studied (Hanson 1969, Bishara *et al*. 1971, Chen and Nawy 1994, Nawy and Chen 1998, Svecova and Razaqpiir 2000, Banthia *et al*. 2003, Liang *et al*. 2016).

In this study, experiments are performed to investigate the performance of concrete beams reinforced with CFRP prestressed prisms under reverse cyclic loading.The failure mode, hysteretic loops, ductility, energy dissipation capacity, stiffness degradation of concrete beams reinforced with CFRP prestressed prisms was studied.

2. Experimental programme

2.1 Materials

In this test, CFRP rebar with diameters of 7 mm was adopted, HPB235 plain rebar with diameters of 8 mm was used for the transverse stirrups, and HRB335 ribbed rebar with diameters of 12 mm and 22 mm were used for the tension reinforcement and compression, respectively. Table 1 lists the mechanical properties of the rebars adopted in the beams.

A typical geometry of the prestressed prism that was used in this experimental investigation is shown in Fig. 1. The prisms were made of reactive powder concrete (RPC) with a compressive

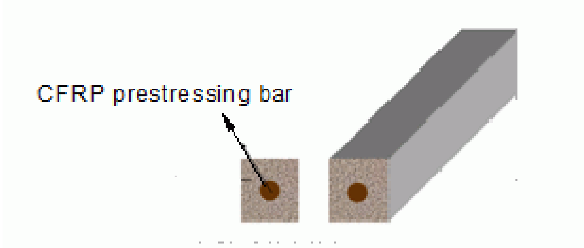


Fig. 1 Typical CFRP prestressed concrete prism(PCP)

Table 1 Mechanical properties of rebars

Reinforcement type	Diameter d/mm	Yield strength f_y/MPa	Ultimate strength f_u/MPa	Elasticity modulus E_s/MPa
Steel bar	8	235	370	2.1×10^5
Steel bar	12	360	550	2.0×10^5
Steel bar	22	365	560	2.0×10^5
CFRP bar	7	------	2200	1.5×10^5

Table 2 Reinforcement details of all tested beams

Beam number	Tension reinforcement	Prestress (kN)	Cross section of PCps(mm)	Compressive reinforcement	Stirrup	
					Mid-span	Shear span
CB1	2ϕ22	——	——	2ϕ22	Φ 8@200	Φ 8@100
PB2	1 Φ 7CFRP+2ϕ12	35	——			
PB3	1PCPs+2ϕ12	35	40×40			
PB4	1PCPs+2ϕ12	43	40×40			
PB5	1PCPs+2ϕ12	35	60×40			

strength of 154 Mpa and a tensile strength of 17.4 Mpa. Prims were concentrically prestressed by a single CFRP rebar. The jacking stresses varied from 880 Mpa to 1320 Mpa, which are equal to 0.40 to 0.60, respectively, of the guaranteed tensile strength. All beams were cast with normal-strength concrete with a compressive strength of 48.8 Mpa and a tensile strength of 2.8 Mpa.

2.2 Design and fabrication of specimens

Five beams were fabricated with 200 mm×300 mm cross sections and spans of 3.6 m.The design parameters of beams were tension reinforcement type, cross section of CFRP prestressed concrete prism, the level of effective prestress, their parameters are presented in detail in Table 2. Fig. 2 shows the typical dimensions for the specimens.

2.3 Test devices of and methods

Each beam was loaded under four-point bending with loading points symmetrically placed about the midplane of the beam at 1000 mm apart. In the test, vertical loading was applied by an electro-hydraulic servo test machine with a load capacity of 500 kN. The test set-up is shown in Fig. 3. The vertical loading procedure included two main steps, namely, a load-controlled step and a displacement-controlled step, which are illustrated in Fig. 4.

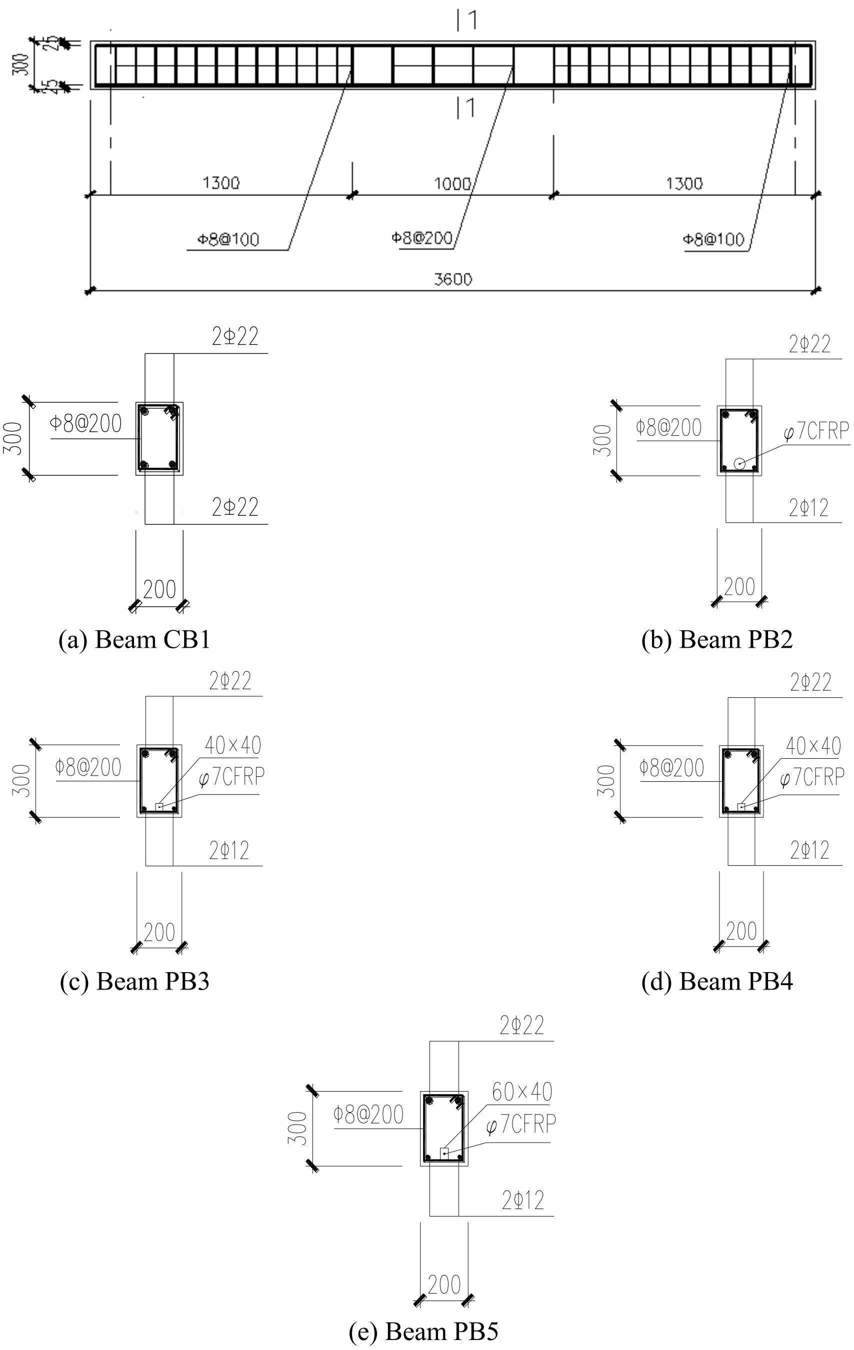


Fig. 2 Typical dimensions and geometry of tested beams

Fig. 3 Test setup

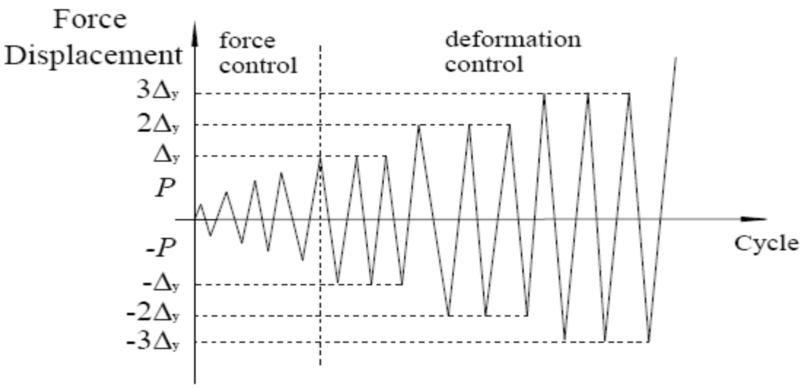


Fig. 4 Loading procedure of test beams

To measure the slab deflection, the linear variable displacement transducers (LVDTs) were placed under the load points and at midspan of beams. In addition, LVDTs were placed at both ends of the beams to measure the possible of tilting. Electrical resistance strain gauges were used to measure the strain in the transverse stirrups, the tension and compression reinforcement. Strain gauges were also used to monitor strain in concrete.

3. Results and discussion

3.1 Failure mode

The failure modes of the beams are shown in Fig. 5. All can be summarized as flexural failures, which can be described as follows:

In the early stage of loading, the beams were elastic and showed no cracks on the surfaces. As the loads increased, tiny cracks first appeared in the pure flexural region, and then some cracks appeared in the flexural-shear region. The numbers of cracks increased with the increase of the load. And some cracks gradually extended. When the load reached crack load, new cracks appeared in the pure flexural region, the flexural-shear region and at the loading point. The width of original cracks was widen, the largest value of that was greater than 0.2 mm. As the loads continued to increase, the cracks developed slowly. After the yield load, some cracks penetrated through completely, and the latter formed cracks became longer and wider. After the beams reached the maximum load, concrete cover fell off continually. Finally, the beams were failure, for the ordinary reinforcement concrete beam, concrete crushing after steel bars yielded (Beam CB1,

(a) Beam CB1

(b) Beam PB2


(c) Beam PB3

(d) Beam PB4

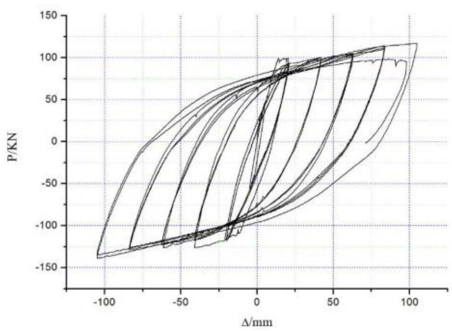
(e) Beam PB5

Fig. 5 Failure modes of the test beams

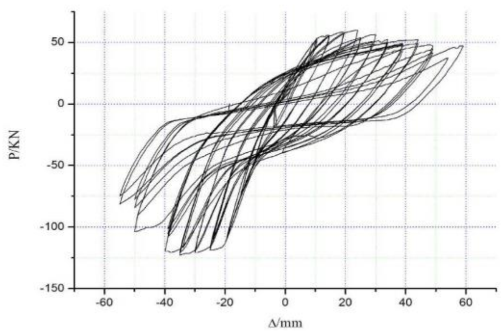
Fig. 5(a)); for the concrete beams reinforced with CFRP bars, slip of CFRP bar after the yielding of steel bar followed by concrete crushing (Beam PB2, Fig. 5(b)); for the concrete beams reinforced with concrete beams reinforced with CFRP prestressed prisms, the CFRP ruptured after concrete beams reinforced with CFRP prestressed prisms (Beam PB3, Fig. 5(c), Beam PB4, Fig. 5(d) and Beam PB5, Fig. 5(e)).

3.2 Hysteretic loops

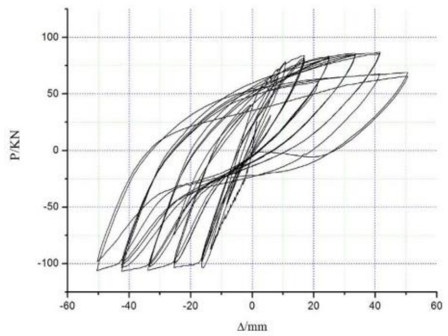
Fig. 6 shows the hysteresis loops observed in the tests, which illustrate the relationship between the cyclic loads and displacements at the midspan of the beams. Based on Fig. 6, the following



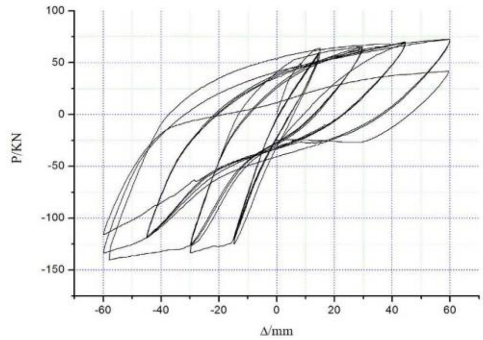
(a) Beam CB1



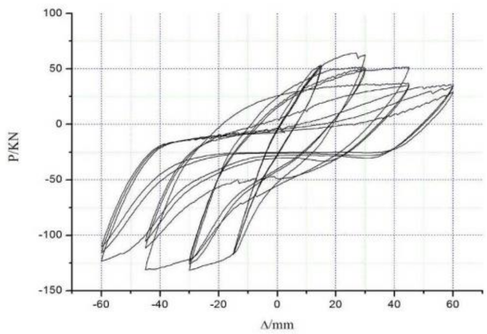
(b) Beam PB2



(c) Beam PB3



(d) Beam PB4



(e) Beam PB5

Fig. 6 Hysteresis loops of the test specimens observations can be made:

(1) In the early stage of loading (before cracking), the loads and displacements have linear elastic stage. And the area of the hysteresis loops was very small and narrow. At the same time, the stiffness degradation was not obvious, the residual deformation was very small.

(2) In the elasto-plastic state, as cracks appeared, the slopes of the hysteresis loops began to decrease, and a large residual deformation when the load was removed. In the displacement-control stage, the hysteresis loops of the beams became larger and wider as the displacements increased. Hysteresis loop were even more fullness, the residual deformation was obvious, and the stiffness and strength of the beams degraded obviously.

(3) In the positive uploading stage and the negative loading stage, comparing with the ordinary reinforcement concrete beam, the hysteresis loops of concrete beams reinforced with CFRP prestressed prisms were less plump. But in the negative uploading stage and the positive loading stage, as was the ordinary reinforcement concrete beam, the hysteresis loops of concrete beams reinforced with CFRP prestressed prisms were plump . In a word, it showed that the concrete beams reinforced with CFRP prestressed prisms had good seismic performance.

3.3 Skeleton curves

A skeleton curve reflects the relationship between the peak loads and the corresponding displacements from the hysteresis loops of the test specimen. The skeleton curves of the specimens are shown in Fig. 7. It shows that the skeleton curves of the specimens were almost linear before cracking, indicating that the beams were in the elastic stage. After cracking, the skeleton curves of the beams became nonlinear, which indicated that the stiffness of beams declined gradually and that the beams were in the elastic-plastic stage. After the peak load, the skeleton curves of the beams entered the softening stage. According to the mechanical characteristics of the test beams, the skeleton curve was divided into three stages: elastic stage, elastic-plastic stage and failure stage.

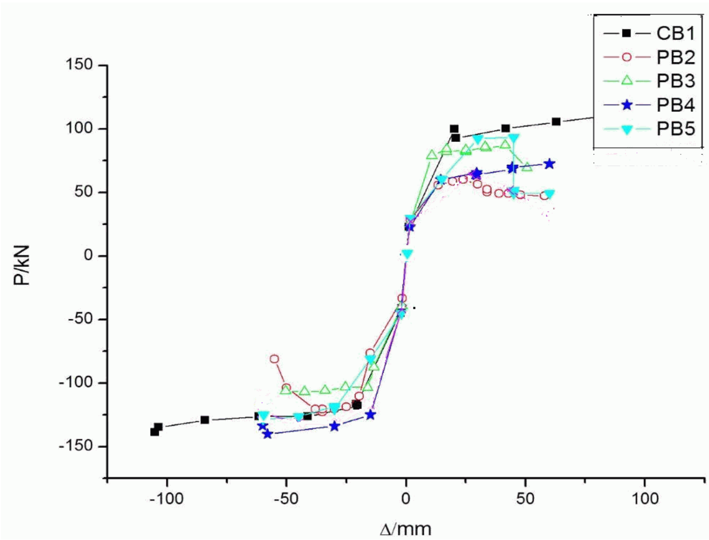


Fig. 7 Skeleton curves of test specimen

The skeleton curves present the concrete beams reinforced with CFRP prestressed prisms have high bearing capacities and stiffnesses under cyclic load. Compared with concrete beams reinforced with CFRP bars, the concrete beams reinforced with CFRP prestressed prisms have higher bearing capacities and stiffnesses.

3.4 Ductility

Table 3 shows the characteristic displacement and displacement ductility coefficient of test beams. Δ_{cr}, Δ_{y}, Δu stands for the crack displacement, the yield displacement and the failure displacement corresponding to the crack load, the yield load and the failure load, respectively. In addition, displacement ductility represented by displacement ductility coefficient, which was defined as $\mu=\Delta_u/\Delta_y$.

From Table 3, it is shown that the displacement ductility coefficients positive and negative directions of concrete beams reinforced with CFRP prestressed prisms (i.e., beam PB3, PB4, PB5,) were from 3.8 to 5.3, and the average ductility factor value in positive and negative direction was 4.2 and 4.4, respectively, which indicates the good seismic performance. And Table 4 reveals that concrete beam reinforced with CFRP prestressed prisms has better ductility than that of concrete beam reinforced with CFRP bars.

3.5 Stiffness degradation

Fig. 8 shows the degradation of the secant stiffnesses of the test beams under low cyclic reversed loading. The stiffnesses of most of the beams decreased slowly during the initial stage of loading. When cracks appeared in the specimens, the stiffnesses decreased dramatically, and when the beams were in the yield stage, the stiffnesses decreased significantly. After the yield point, the stiffnesses degradation tend to be slow and show no obvious abrupt change.

In addition, Fig. 8 shows that the CFRP prestressed prisms can enhance the stiffness of the concrete beams, the stiffness in positive and negative direction of concrete beams reinforced with CFRP prestressed prisms was higher than that concrete beam reinforced with CFRP bars.

Table 3 Characteristic displacement and displacement ductility coefficient

Beam no.	Loading direction	Crack point	Yield point	Failure point	Ductility coefficient
		Δ_{cr}/mm	Δ_y/mm	Δ_u/mm	μ
CB1	Positive	1.3	20.6	105.1	5.1
	Negative	1.7	18.3	105.1	5.7
PB2	Positive	1.8	19.1	58.0	3.3
	Negative	1.5	18.5	55.0	2.9
PB3	Positive	1.5	10.8	50.6	4.7
	Negative	1.8	13.5	50.5	3.8
PB4	Positive	1.7	15.1	60.1	3.9
	Negative	2.3	11.4	60.0	5.3
PB5	Positive	1.9	15.0	60.0	4.0
	Negative	1.7	15.0	60.0	4.0

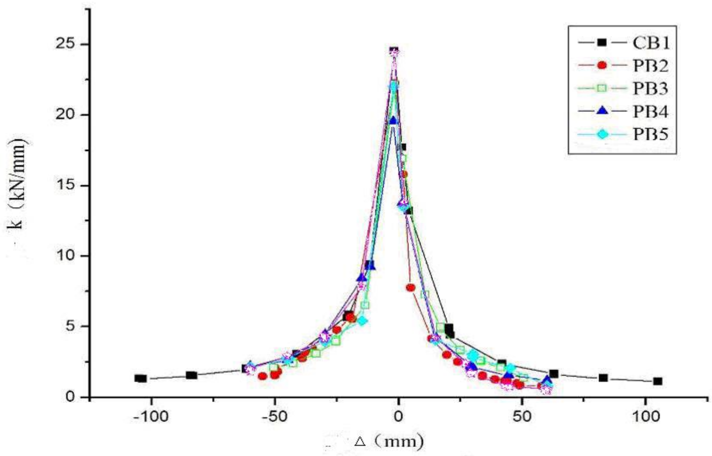


Fig. 8 Stiffness degradation of test beams

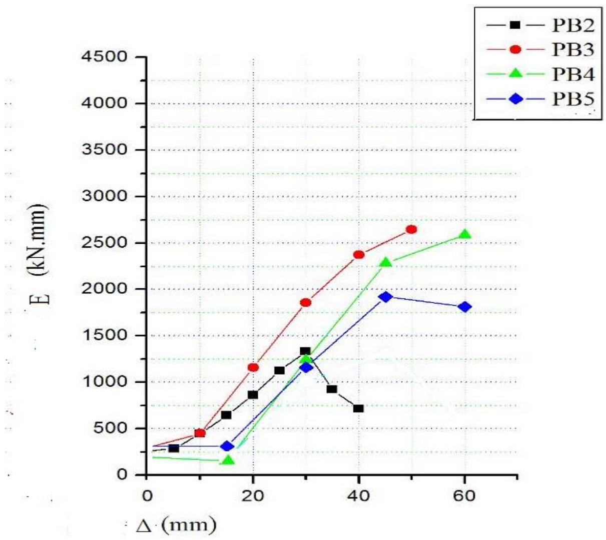


Fig. 9 Cumulative energy dissipation of test beams

3.6 Energy dissipation capacity

Fig. 9 shows the cumulative energy dissipation of test beams. It can be seen that the value of dissipated energy is the least for concrete beam reinforced with CFRP bars, indicating this type beams have bad seismic performance than concrete beams reinforced with CFRP prestressed prisms. Compared beam PB3 with beam PB4, positive energy dissipation value of beam PB3 at the same displacement is obviously higher than that of beam PB4. It shows that the increase of level of pretress of CFRP prestressed prisms can't improve energy dissipation capacity of concrete beams reinforced with CFRP prestressed prisms. Compared beam PB3 with beam PB5, energy dissipation value of beam PB3 at the same displacement is obviously higher than that of beam PB5. It shows that the increase of cross section of CFRP prestressed prisms can't improve energy dissipation capacity of concrete beams reinforced with CFRP prestressed prisms.

5. Conclusions

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

• The concrete beams reinforced with various reinforcement, including ordinary steel bars, CFRP bars and CFRP prestressed concrete prisms(PCP) have a little different on the failure characteristics. But the failure mode of that beams can be classified as flexural failure.

• The concrete beams reinforced with CFRP prestressed prisms have good seismic performance. Comparing with the concrete beam reinforced with CFRP bar, the hysteresis loops of concrete beams reinforced with CFRP prestressed prisms were more plump.

• The concrete beams reinforced with CFRP prestressed prisms have high bearing capacities and stiffnesses under cyclic load

• With the increase of level of pretress and cross section of CFRP prestressed prisms, it can't improve the energy dissipation capacity.

Acknowledgments

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