Experimental study of precast BFRP-wrapped segmental concrete columns with external ED device under eccentric cyclic loading

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Abstract

Precast segmental concrete column has been proposed to reduce construction time and improve construction quality. Its applications are mainly limited in areas of low seismicity because of a lack of knowledge on its seismic performance. Many previous studies investigated the seismic behaviour of segmental columns under cyclic loadings. All of them applied centric lateral loadings on the column. However, the column may experience torsional moment under earthquake excitations due to irregular geometry, and spatial variation of seismic ground motion. Investigations on the seismic behaviour of segmental columns under torsional moment in addition to bending moment are very limited. This paper investigates the performances of basalt fibre-reinforced polymer (BFRP) wrapped segmental concrete columns with external energy dissipation (ED) devices under eccentric cyclic loading. Four segmental columns with or without BFRP wrap and with or without external ED devices were tested under centric or eccentric cyclic loadings. The testing results show that the eccentric loading causes more damage to the column; by wrapping the concrete segments with BFRP, the damage of the column is minimized and the ductility of the column is improved; and the use of external ED devices increases the energy dissipation of segmental columns.

Keywords: segmental column; seismic behaviour; eccentric; cyclic loadings; BFRP; ED devices.

1. INTRODUCTION

Traditional cast-in-place construction method often causes traffic disruption and environmental impact. In addition, it always involves a large number of construction activities onsite. The quality control and safety for the construction crew are also challenges due to the site working conditions. To overcome these problems, prefabricated construction has become popular around the world. The precast segmental column is a substructure which is commonly used in prefabricated construction. It normally includes precast concrete segments and posttensioned tendons. The on-site construction activities only contain installing the precast segments and applying the posttensioned forces to clamp the segments. As a result, the construction time can be significantly reduced. It is a promising solution for rapid construction demand in congested urban areas. However, its applications are limited to low seismic areas due to a lack of knowledge on its seismic performance (Ou et al. 2009).

Many experimental and numerical studies have been carried out to investigate the seismic performance of precast segmental column (Billington and Yoon 2004, Hung et al. 2017, Li et al. 2017a, Li et al. 2017b, Zhang et al. 2016). Only the centric cyclic loading was considered in previous studies. However, due to the irregular geometry of the bridge and the spatial variation of the ground motion, bridge columns may experience torsional moments in addition to shear forces and bending moments under earthquake ground excitations. Some studies that considered torsional moment have been carried out on monolithic RC columns (Prakash et al. 2010), concrete filled steel (CFST) columns (Nie et al. 2013), and thin-wall steel members (Hsu and Shyu 2001). However, study that has considered the effects of torsional moment on the cyclic performance of precast segmental columns is limited. Therefore, it is necessary to investigate the performance of precast segmental columns under eccentric loading.

Concrete crushing damages at the column joints were commonly observed in the previous tests of the precast segmental columns (Wang et al. 2008). To mitigate the damages, strengthening methods such as using high performance concrete (Billington and Yoon 2004), and confining the segments with steel jacket (Hewes and Priestley 2002) were proposed and examined. Recently, basalt fibre has attracted increasing attention because of its low cost and good mechanical properties. In this study, basalt fibre-reinforced polymer (BFRP) was adopted to strengthen the concrete segments.

Previous studies revealed that the segmental column with only unbonded tendon across the joint showed very good ductility and outstanding self-centring ability. However, the energy dissipation capacity of the column was low (Ou et al. 2009). To increase the energy dissipation absorption ability of the segmental column, energy devices including internal mild steel bars (Guerrini et al. 2015) and external energy dissipation devices (ElGawady and Sha’lan 2010) were proposed and investigated. However, the use of energy dissipation devices may increase the residual displacement due to plastic deformation of the devices. In this study, specially designed tension-only external energy dissipation devices were proposed to increase the energy dissipation and reduce the residual displacement.

This study experimentally investigates the performance of segmental concrete columns with or without BFRP wrap, and with or without external energy dissipation (ED) devices under centric or eccentric cyclic loading. The test results are presented and analysed in terms of the damage mode of the column, hysteretic curve and energy dissipation capacity of the column. The effect of BFRP wrapping on mitigating the concrete damage and the effects of the proposed tension-only external ED device on energy absorption capacity of segmental columns are evaluated.

2. EXPERIMENTAL PROGRAM

Four specimens were designed and constructed. The schematic drawing are shown in Fig. 1. The total height of the column is 800 mm and the cross section is 100×100 mm. The dimensions of the columns were chosen based on the capacity of the available equipment. Each column consists of five segments with the same height. Four transverse stirrups with a diameter of 4 mm were used and four longitudinal steel bars with 6 mm diameter were used to hold the transverse reinforcements. The longitudinal steel bars were discontinued at the segment joints which means the joints between the segments were free to open when the column deforms laterally. Two starter bars with 6 mm diameter were used to connect the bottom segment with the footing. A seven-wire high strength prestress strand with an area of 54.7mm^2 was used to clamp all the segments together. The corresponding prestressing tendon steel ratio was 0.547%. Previous study also showed that shear keys were necessary between segments to resist possible shear slip at the joint under different kinds of loadings such as cyclic loading and impact loading (Li et al. 2017b, Zhang et al. 2016). However, it was also observed that large concrete shear keys also increased stress concentration which results in more serve damage in the segments. To minimize the stress concentration and improve the shear resistance of the column, as shown in Fig. 2 (a), dome-shaped shear keys were introduced in this study. The design details of the tested columns are summarized in Table 1. The columns were named based on the design details including the loading conditions (C/E), BFRP wrapping conditions (Y/N) and energy dissipation devices (N/E). For example, the column E-Y-E means this column was loaded with eccentric cyclic loading (E), strengthened with BFRP (Y) and with external ED devices (E).

The first column C-N-N was a reference column which was designed to represent the segmental column under centric lateral cyclic loading, i.e. the most commonly studied loading case without generating torque in the column. The specimen E-N-N was a column with the same design as the first one, but was used for testing under eccentric cyclic loading. A schematic drawing of the eccentric loading is shown in Fig. 2 (b). The eccentric distance "e" shown in Fig. 2 (b) is 34 mm, which is restricted by the testing system. The third column was loaded with the same eccentric loading as that of the second column, the column segments were wrapped with BFRP to strengthen the concrete segments and reduce the concrete damage. The fourth column E-Y-E uses the BFRP wrapping and also the specially designed tension-only external energy dissipation devices. The design of the ED plates is shown in Fig. 2 (c). The columns were prepared and cast in the lab. The material properties are shown in Table 2. The columns were then installed and tested under cyclic loading. Fig. 3 shows the setup of the testing system. The total top mass is 455 kg and the prestressing force in the tendon is 30kN. The lateral cyclic loading protocol is shown in Fig. 4.

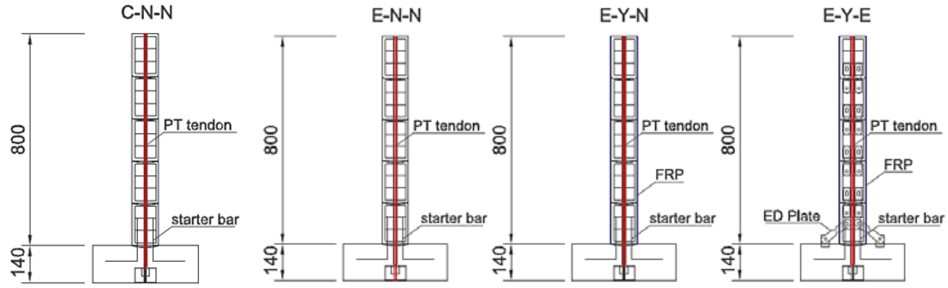
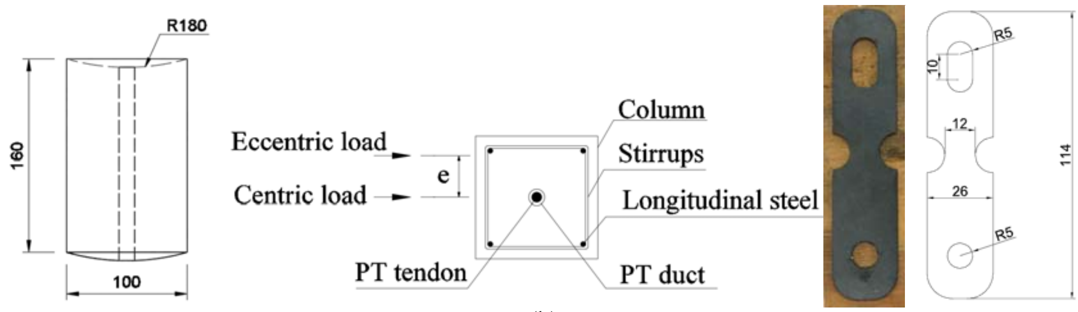


Fig. 1 Schematic of the specimens (Unit:mm)

Table 1 Summary of the specimens

No.	Name	Loading	BFRP	ED	Height (mm)	Cross section (mm × mm)
1	C-N-N	Centric	No	No	800	100 × 100
2	E-N-N	Eccentric	No	No	800	100 × 100
3	E-Y-N	Eccentric	Yes	No	800	100 × 100
4	E-Y-E	Eccentric	Yes	External	800	100 × 100



(a) (b) (c)

Fig. 2 Schematic of the (a) Dome-shaped shear key; (b) Centric and eccentric loadings; (c) External ED device (Unit:mm)

Table 2 Properties of the materials

Material	P (kg/m3)	E (GPa)	f_c' (MPa)	f_t or f_y (MPa)
Concrete	2400	30	34	5
Longitudinal rebar	7800	200	-	500
Stirrup	7800	200	-	300
ED plate	7800	200	-	300
BFRP	2650	105	-	2300
Prestress tendon	7850	195	-	1860

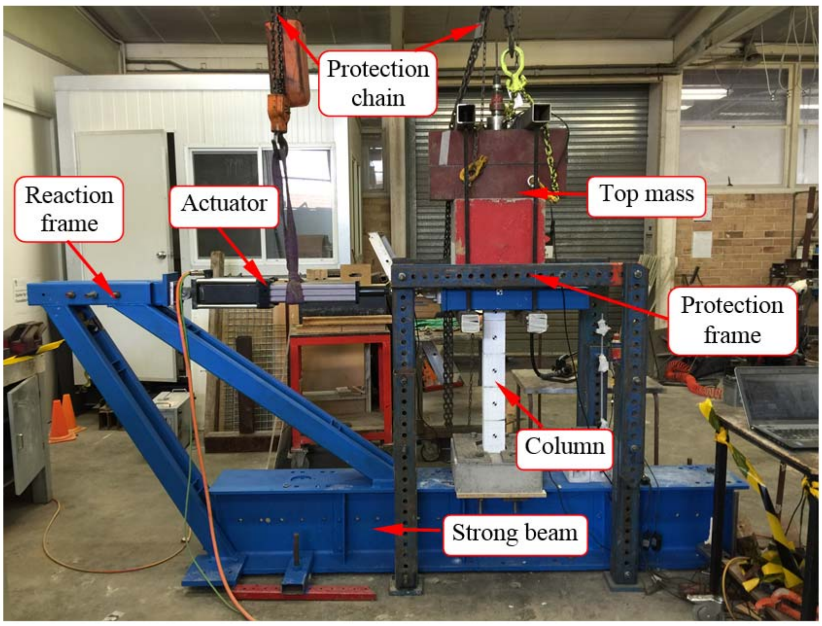


Fig. 3 Test setup

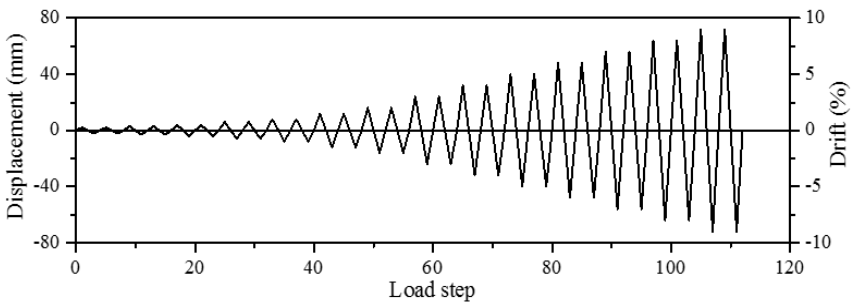
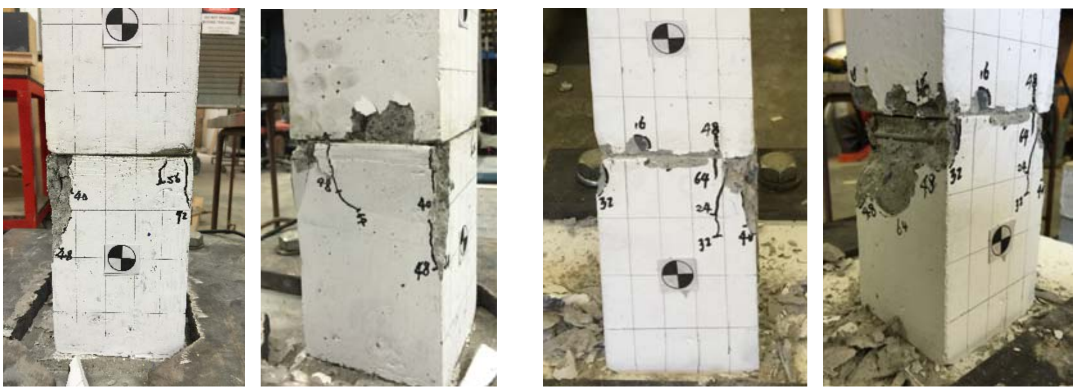


Fig. 4 Loading sequence

3. TEST RESULTS

Fig. 5 shows the damage of the columns after the test. The damages concentrated near the joint between the bottom segments because the bottom segment was connected to the footing with two starter bars and thus openings were concentrated at the joint between the bottom two segments. The concrete near the joint openings experienced excessive compressive stress which caused cracks and spalling damages at the joint. Compare Fig. 5 (a) and (b), it can be observed that the column E-N-N under eccentric loading experienced more damage. This observation indicates that the eccentric loading generates extra torsional moment in addition to bending moment and shear force in the column and causes more damage to the concrete segments. Fig. 5 (c) shows the results of the column with BFRP wrapped segments. No concrete damage was found, indicating that BFRP wrapping is effective to prevent the concrete spalling damage under cyclic loading. Fig. 5 (d) shows the column E-Y-E with BFRP wrapped segments and external ED devices. Similar to the column E-Y-N, the column E-Y-E with BFRP wrapping also experiences limited damage. Besides, the tension-only ED devices deform and recover without any buckling, which provide the column with extra energy dissipation capacity and maintain the residual displacement of the column small. Fig. 6 shows the hysteretic curves of the specimens. It can be observed that the strength of the column E-N-N under eccentric loading drops significantly compare with that of the column C-N-N under centric loading. This is because the column experiences more damage as discussed above. Compare the hysteretic curves of the column E-N-N and E-Y-N, as shown in Fig. 6 (b) and (c), it can be seen that the use of BFRP effectively increases the ductility of the column. Meanwhile, since limited damage was observed in the column E-Y-N, the area of the hysteretic curve is small, indicating small energy dissipation capacity, which is shown in Fig. 7. The hysteretic curve of the column E-Y-E is shown in Fig. 6 (d). It can be observed that the strength of the columns is increased compared with that of the column E-Y-N without ED devices. The energy dissipation is also increased as shown in Fig. 7.



(a) (b)

(c) (d)

Fig. 5 Damage of the columns (a) C-N-N, (b) E-N-N, (c) E-Y-N, (d) E-Y-E

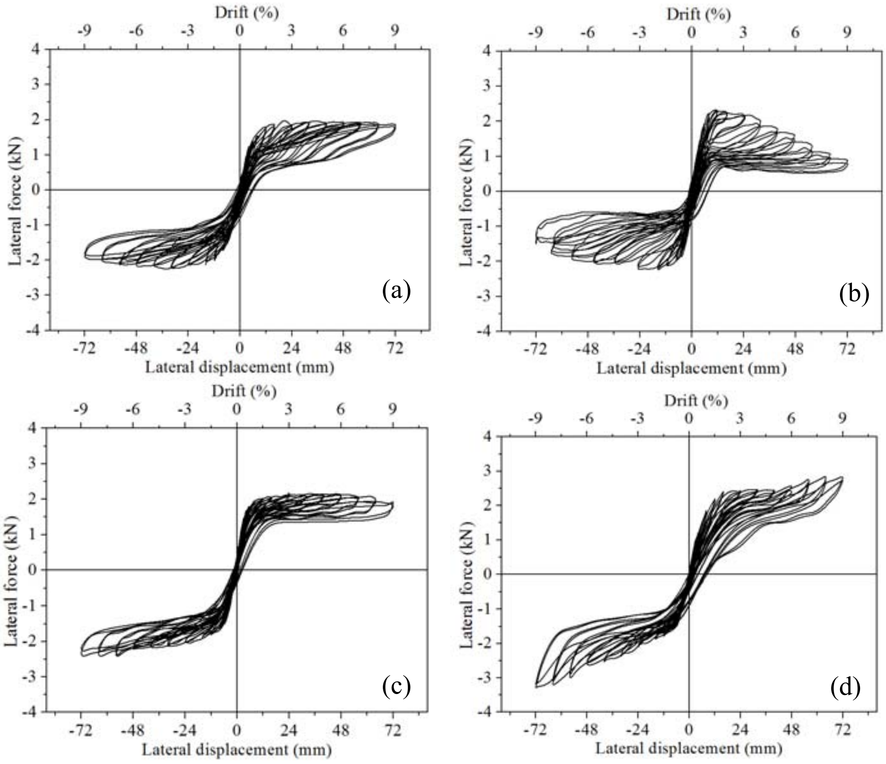


Fig. 6 Hysteretic curves of the columns (a) C-N-N, (b) E-N-N, (c) E-Y-N, (d) E-Y-E

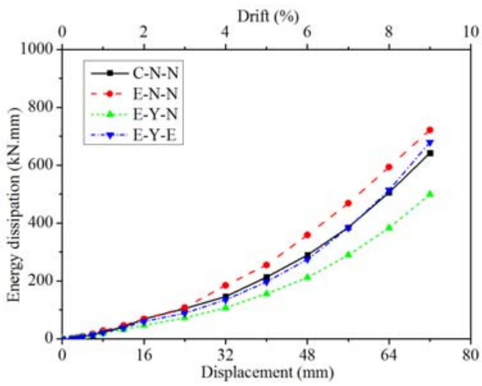


Fig. 7 Cumulative energy dissipation of the columns

4. CONCLUSIONS

This paper experimentally investigated the performance of precast segmental columns under centric or eccentric cyclic loading. BFRP was used to confine the segments and reduce the concrete cracks and spalling damage. Tension-only external ED devices were also designed to increase the energy dissipation capacity of the precast segmental columns. Based on the experimental results and analyses, it is concluded that the eccentric loading caused more damage to the column and the use of BFRP was effective to reduce the damage of the segments and improve the performance of segmental columns. Using tension-only external ED devices increased the strength and also the energy dissipation capacity of the column.

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