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# CYCLIC TESTS OF PRECAST SEGMENTAL CONCRETE COLUMNS WITH UNBONDED POST-TENSIONED TENDONS

C. Li[(1)*], H. Hao[(2)], X. Zhang[(3)]

[(1)*] *PhD candidate, Department of Civil Engineering, Curtin University, Chao.li11@postgrad.curtin.edu.au*
[(2)] *John Curtin Distinguished Professor, Department of Civil Engineering, Curtin University, Hong.Hao@curtin.edu.au*
[(3)] *Research Associate, Department of Civil Engineering, Curtin University, Xihong.Zhang@curtin.edu.au*

## *Abstract*

Precast segmental concrete column has been used in building and bridge constructions due to its numerous advantages, including accelerated construction speed, less construction site disruption, better construction quality control and less environmental impacts. Its applications are, however, still limited because knowledge about its performance under seismic loading is not enough. Many tests have been reported, but usually on different designs. Also, previous studies focused on testing cantilever-type precast segmental columns, i.e., with only the bottom end of the column fixed. This paper presents a comparative study through testing one monolithic RC column used as the reference, and four segmental columns with different designs to systematically study the influences of 1) placement of energy dissipation (ED) bars; 2) shear keys; and 3) number of segments, on the performance of the segmental columns subjected to cyclic loadings. To be different from the boundary condition of previous studies, rotational freedom of the top end of the columns is restrained in this study. The performance of each design with respect to the reference monolithic RC column in terms of the lateral strength capacity, hysteretic behavior and energy absorption capacity is examined. It was found that adding ED bars could increase the energy dissipation of the segmental column, but lead to larger residual deformation. Concrete shear keys were able to prevent the slip between the segments, but severe damage could occur due to stress concentration surrounding the shear keys. The number of segments had insignificant influence on the performance of segmental column. Further study will be carried out to improve the identified shortcomings so as to derive better performing segmental columns for practical applications in constructions in seismic regions.

*Keywords: precast segmental column; cyclic test; seismic performance; tendons*

## 1. Introduction

In the past decade, precast segmental column has attracted a lot of research interests around the world. Compared with traditional cast-in-place construction, precast segmental column has several innate advantages. The reason is that the construction methods of traditional cast-in-place column and precast segmental column are totally different. For the cast-in-place construction, all the construction work including building the working platform, placing the structural forms and casting concrete need to be done onsite. In contrast, for the precast segmental column, the concrete segments are precast in prefabricate factories and then transported to the construction site. Then the segments are erected quickly and efficiently onsite. Due to the fast construction speed onsite, the precast segmental column can reduce the traffic disruption especially in busy urban areas. In addition, since the prefabrication environment is better in the workshop, the quality of precast segments can be better controlled, and novel materials such as fiber reinforced concrete which is hard to mix onsite can be used in precast segmental columns. Despite all these advantages, the applications of precast segmental column are still limited to low seismic regions, because its seismic performance is not well known yet. In recent years, intensive researches have been carried out to study its performance under earthquake loading [1-8].

Typical segmental column normally comprises several precast concrete segments and prestressing tendons which clamp all the segments together. Previous studies showed that this kind of segmental column showed limited energy dissipation [2, 9]. Different energy dissipation systems, including internal and external devices were developed to increase the energy dissipation capacity of the precast segmental column. Ou et al. adopted internal mild steel reinforcement between adjacent segments as energy dissipation bars and the results showed that the energy dissipation (ED) bars could increase the energy absorption capability of the column remarkably [9]. Marriott et al. proposed external devices which connected the base segment with the footing to increase the energy dissipation capacity of the segmental column [10]. The results demonstrated that the external energy dissipation devices were effective in increasing the energy dissipation capacity of the column. In this study, column with and without ED bars were tested to investigate the general behavior of segmental column without ED bars and also the effectiveness of ED bars to increase the energy dissipation capacity of segmental columns.

Precast segmental column normally consist of multiple segments. Under lateral loading, openings will be formed at the joints between the segments. With different numbers of segments, the behavior of openings such as opening position and opening size may be different. ElGawady and Sha'lan carried out experimental study on precast segmental bridge bents [11]. One specimen consisted of one segment and another one consisted of three segments. Test results showed these two specimens behaved very similarly. Since only limited studies were carried out on the influence of segment number on the performance of precast segmental column, investigation on this factor is necessary.

In the segmental column system, the joint interfaces could be critical to the performance of segmental column in terms of the shear resistance capacity of the column. Compared with monolithic RC columns, shear force in the segmental column is mainly transferred through the friction force between the segments joints. Some previous study showed that the shear force can be fully restrained by friction force [2]. However, shear slip between segments was reported by some other researchers [12]. The effect of shear key on segmental column under earthquake loading has not been well studied.

In order to investigate the performance of segmental column under cyclic loading, four segmental columns with different designs were tested. Another monolithic column was also designed and tested as a reference column. The aims of this study are to systematically investigate the inelastic behaviour of precast segmental columns and to examine the influences of different designs including the ED bars, number of segments and concrete shear keys on the cyclic performance of segmental columns.

## 2. Experimental setup

Five specimens including one monolithic column and four segmental columns were investigated in this study. Fig. 1 shows the schematic drawing of the specimens. The dimensions of the specimens were chosen based on the available instruments. The specimens were fabricated at quarter scale. The columns were named according to their design details. For instance, the second column was named as 5seg which consisted of five plain segments. The third column 5segED consisted of five segments with ED bars across segmental joints. The fourth column 7seg included seven segments. And the fifth column 7segkey had seven segments and shear keys between the segments. Fig. 2 shows the cross sections of the tested specimens. Four continuous ribbed mild steel bars with a diameter of 6mm were used as the longitudinal reinforcement for the monolithic column. The longitudinal steel ratio was 1.13%. All the segmental columns used the same longitudinal reinforcement bars but the reinforcements were discontinuous at the segment joints. Two starter bars with a diameter of 6mm were used to connect the base segment to the footing in the lateral loading direction. For all the segmental columns, an unbonded prestress tendon was placed in the duct which was embedded at the center of each column. The transverse stirrup was made of plain mild steel with a diameter of 4 mm. The distance between each stirrup was 40mm. Table 1 shows the details of the five columns. Table 2 summarizes the material properties of the tested specimens.

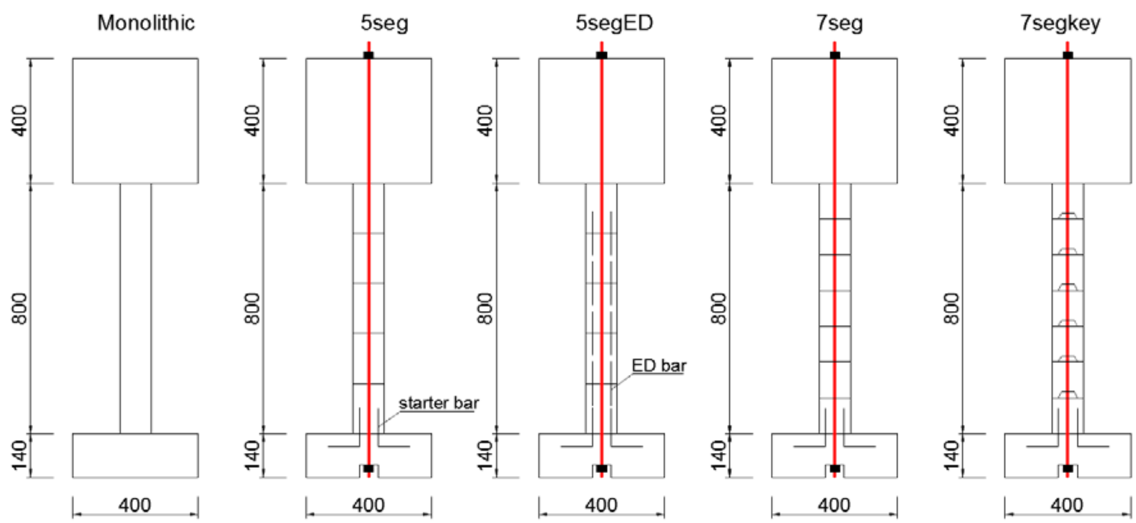
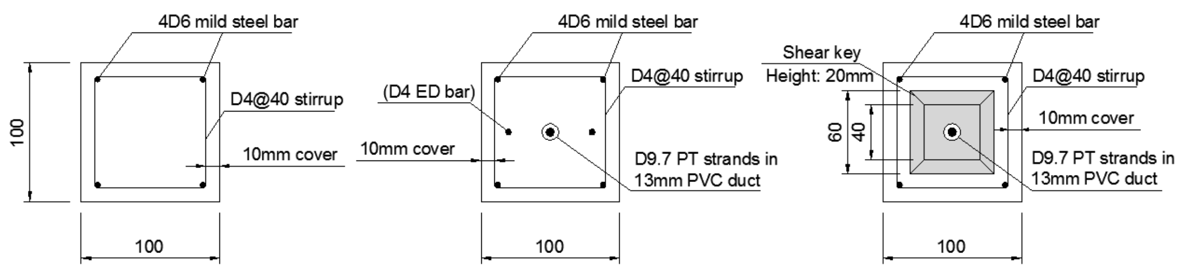



Fig. 1 Specimen schematic drawing




(a) (b) (c)

Fig. 2 Section details: a). monolithic; b). 5seg, 5segED and 7seg; c). 7segkey

Table 1 Summary of specimen designs

| No. | Name | Height (mm) | No. of segments | Reinforcement | | | | *PT force(kN) |
|---|---|---|---|---|---|---|---|---|
| | | | | Longitudinal | ρ(%) | Transvers | ρ(%) | |
| **1** | Monolithic | 800 | - | 4D6 | 1.13 | D4@40 | 1.57 | - |
| **2** | 5seg | 800 | 5 | - | - | D4@40 | 1.57 | 30 |
| **3** | 5segED | 800 | 5 | 2D4 (ED bars) | 0.25 | D4@40 | 1.57 | 30 |
| **4** | 7seg | 800 | 7 | - | - | D4@40 | 1.57 | 30 |
| **5** | 7segkey | 800 | 7 | - | - | D4@40 | 1.57 | 30 |

*PT stands for prestressed tendon

Table 2 Material properties

| Material | P (kg/m3) | $f_c$' (MPa) | $f_t$ or $f_y$ (MPa) | E (GPa) |
|---|---|---|---|---|
| **Concrete** | 2400 | 34 | 5 | 30 |
| **Longitudinal rebar** | 7800 | - | 500 | 200 |
| **Stirrup** | 7800 | - | 300 | 200 |
| **Prestress tendon** | 7850 | - | 1860 | 195 |

The setup of the testing system is shown in Fig. 3. The testing system was built on a strong steel beam. To restrain the rotation freedom of column top, a 'yielding frame' was designed to hold the top of the column. The yielding frame consists of two hinges, a rigid horizontal beam and a vertical column. The two hinges ensure the frame will 'yield' and provide no reactions to the column. During the test, the footing of the column was fixed on the strong beam. Then the segments were installed one by one. A 450kg top mass was added to the top of the column. The prestress tendon was then stressed with a hydraulic jack. The prestressing force level was controlled by a load cell at the top of the tested specimen. The actuator was supported by a reaction frame on the right hand side of the testing system. During the test, the actuator will apply cyclic lateral load to the columns. The lateral loading sequence is shown in Fig. 4. A load cell was installed in front of the actuator to measure the applied cyclic load. An LVDT was placed behind the column to measure the displacement in the loading direction.

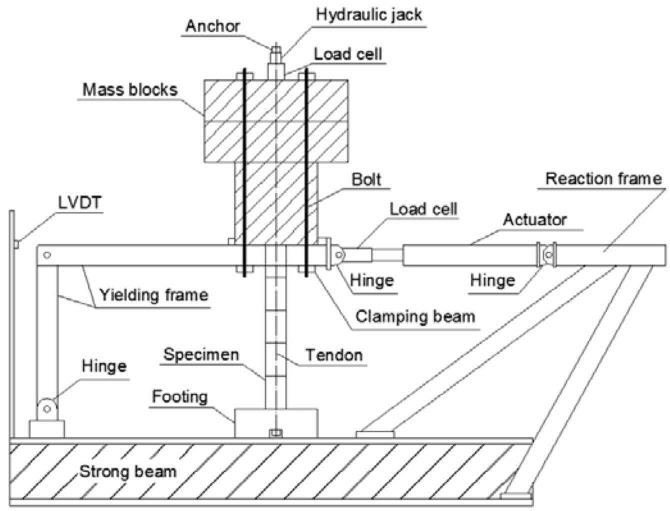



Fig. 3 Experiment setup

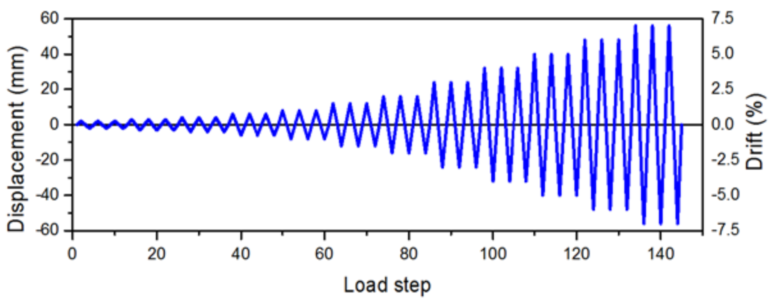



Fig. 4 Loading sequence

## 3. Results and analysis

### 3.1 Column damage

Fig. 5 shows the damage of the monolithic column. During the test, flexural horizontal cracks started to appear at early stage of the test. When the lateral displacement reached 4mm (0.5% drift ratio), the flexural cracks began to form at the column base. More and more cracks were formed along the column as the drift level increased. At 5% drift ratio, due to the damage of concrete and fracture of the longitudinal reinforcement the lateral strength of the column dropped significantly. The test was then stopped at this drift ratio to prevent collapse of the testing system.

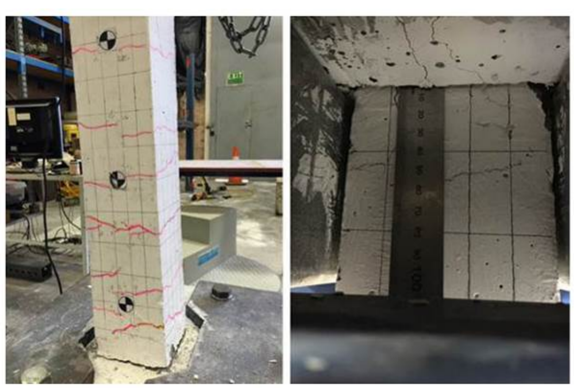


Fig. 5 Damage of the monolithic column (column base and column top)

All of the precast segmental columns showed small residual drift and localized damage. As shown in Fig. 6, for column 5seg under lateral loading the joint openings mainly concentrated at the joint between the base two segment and the joint between the column and the top mass. This is because there were no reinforcement between the segmental joints except the joint between the footing and the base segment. Under double curvature bending, the bending moment at the base and the top of the column were the largest, the joint between the column and added top mass opened first under such large moment. Meanwhile, the starter bars restricted the opening at the footing-column joint to develop. As the drift ratio further increased, the applied moment at the joint between the two bottom segments exceeded the opening threshold, as a consequence, this joint opened instead of the column-footing joint. At 7% drift, severe damage was observed at the base segment and also the top segment due to concrete compressive failure.

Fig. 6 Damage of column 5seg (column base and column top)

The column 5segED behaved differently from the column 5seg without ED bars. The damage pattern of the column 5segED was shown in Fig. 7. Joint opening of this column occurred mainly at the footing-column and the column-mass joints. Damage of the column also located around these two places. No openings were observed at other joints and the other segments remained intact. It was observed that the column behaved like a whole segment which rocked at both the base and the top joints. This is different from column 5seg without ED bars. The reason is that the ED bars across the joints prevented the openings. As the drift ratio increased to 7%, both sides of the base segment were damaged at the toes of the segment. The top segment was also seriously damaged. Under double curvature bending, plastic hinges were developed at both ends of the column. The column failed due to the crushing of the concrete near the footing-column joint and the column-mass joint and also the fracture of starter bar between the footing and the base segment.

Fig. 7 Damage of column 5segED (column base; column top; fracture of starter bar)

The damage of column 7seg was shown in Fig. 8. As shown column 7seg behaved similarly to column 5seg in terms of joint opening locations and damage mode. The base segment was seriously damaged at 7% drift ratio. The covering concrete on the left side of the base segment totally spalled. No damage was observed in other segments. It should be noted that shear slip was found between the two bottom segments, indicating that the friction force between the segments was not sufficient to resist the shear force.

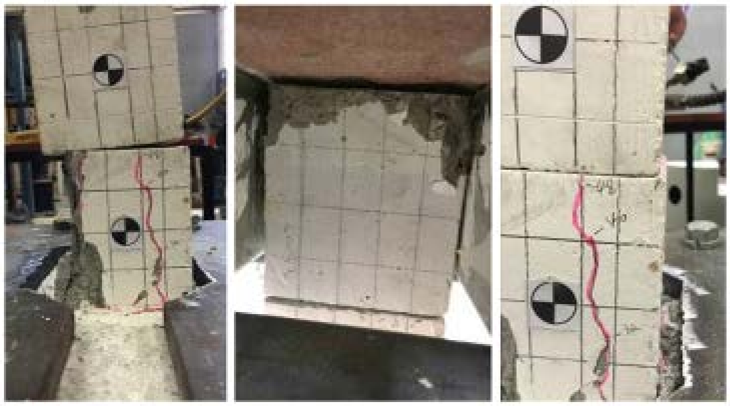


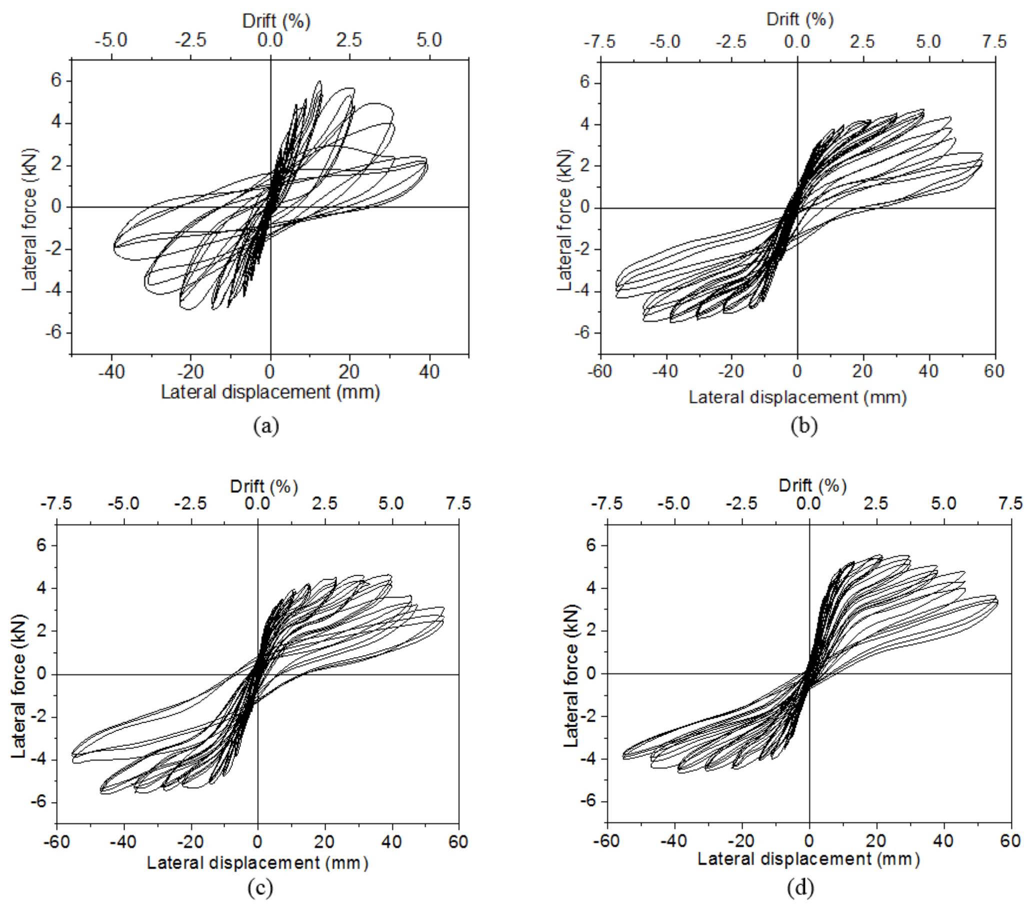
Fig. 8 Damage of column 7seg (column base; column top; slippage between segments)

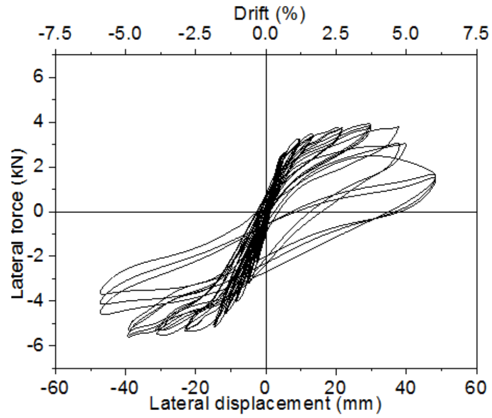
Fig. 9 shows the damage of column 7segkey. This column was designed to investigate the influence of shear keys on the performance of the segmental column. During the test, it was found that except the two bottom segments and the top segment the other segments remained intact. The column was only tested to 6% drift ratio because the two bottom segments were seriously damaged and the strength of the column dropped significantly at this drift. Compared with column 7seg without shear keys, no slip was observed between all the segments, proving that the shear keys were effective to prevent the slippage between segments. Nevertheless, this column experienced more severe damage and its lateral resistance capacity dropped obviously at 6% drift level. The reason could be that the existence of concrete shear key resulted in severe stress concentration, leading to the concrete crushing damage. Therefore, the current shear key may not be a good geometry for shear key design even though it provides shear resistance between adjacent segments. Modified designs of shear keys will be made in the future to minimize stress concentration while providing shear resistance.

Fig. 9 Damage of column 7seg (column base; column top)

## 3.2 Hysteretic curves

The hysteretic curves of all the columns are shown in Fig. 10. For the monolithic column, it reached its maximum strength of 6kN and -4.8kN in the push and pull directions at 2% drift level. The asymmetrical lateral forces were probably caused by unsymmetrical damage of the column during the test in push and pull directions, which is more apparent for small-scale specimens. After this drift level, the lateral loading capacity dropped quickly. The hysteretic curve enclosed a large area, indicating that the column dissipated a large amount of energy. However, the energy absorbed by the monolithic column was owing to permanent plastic deformation of reinforcement and concrete damage. Since there was no prestress tendon in the column, the residual drift of the column was relatively large. The hysteretic curves of all the precast segmental columns showed small residual displacements indicating the segmental columns had better self-centering ability and exhibited better ductility in comparison with the monolithic column. For the column 5seg without ED bars, the maximum strength reached about 4.8kN and -5.5kN for the push and pull directions at the drift level of 5%. After 5% drift level, obvious residual drift and drop of lateral strength could be observed especially for the push side. This was due to the damage of the base segment and the loss of the prestressing force in the tendon. By comparing the hysteretic curve of this column with the monolithic column, the area enclosed by the hysteretic loops was relatively small which indicated that the energy dissipated by this column was smaller than that of the monolithic column. For column 5segED, the residual drift was also small due to the restoring force provided by the prestress tendon. However, the area of the hysteretic loops was larger than that of the column 5seg because of the ED bars placed across the segment joints, indicating that more energy was dissipated by this column. It demonstrated that adding appropriate amount of ED bars could increase the energy dissipation capacity while maintained low residual displacement. This observation is consistent with previous experimental results reported by Ou et al. [9]. The column 7seg also showed outstanding self-centering ability. The residual drift of this column was stable till the end of the test. Possible reason could be that the loss of tendon force was not severe than that of column 5seg. For the column 7segkey, because of severe damage of the two base segments, the strength of the column dropped significantly after 5% drift level. Compared with column 7seg without shear key, column 7segkey experienced more significant damage. As a result, the residual drift was also large compared with other segmental columns. Stress concentration of the shear keys may be the main reason that caused such damage.






(e)

Fig. 10 . Hysteretic curves of: (a) Monolithic; (b) 5seg; (c) 5segED; (d) 7seg; (e) 7segkey

### 3.3 Prestressing force history

As demonstrated above, the post-tensioned tendon in the segmental column helps to improve the self-centering capacity of the column, which significantly reduced the residual displacement of the column. Loss of prestressing force in the tendon could reduce the strength of the column and also the self-centering ability. It is therefore necessary and important to study the behavior of prestress tendon in the segmental column. Possible reasons leading to the loss of prestress force can be as follow: the damage of the segments which shortened the total height of the column, possible slippage of tendon at the anchorage, and damage of concrete near the anchorage zone. Fig. 11 shows the recorded prestress force history versus column drift of the columns under lateral cyclic loading. As shown, for column 5seg due to the damage of the column and possible damage of the anchorage zone, the prestressing force started to drop obviously under repeated loading at 6% drift ratio. The drop of prestressing force decreased the lateral strength of column. For column 5seg, significant prestressing force loss happened at 7% drift. The prestressing force history of column 7seg is unsymmetrical. Serious unsymmetrical damage of the base segment could be the reason. For column 7segkey, as observed in the test the two bottom segments were seriously damaged, significant prestressing force loss started after 5% drift ratio. In summary, the effective prestressing force affected the lateral strength of the segmental column directly. The loss of prestressing force reduced the lateral strength capacity of the column. In practical design of segmental column, the prestressing force and anchorage of the tendon should be particularly concerned to avoid losing of large amount of prestressing force.

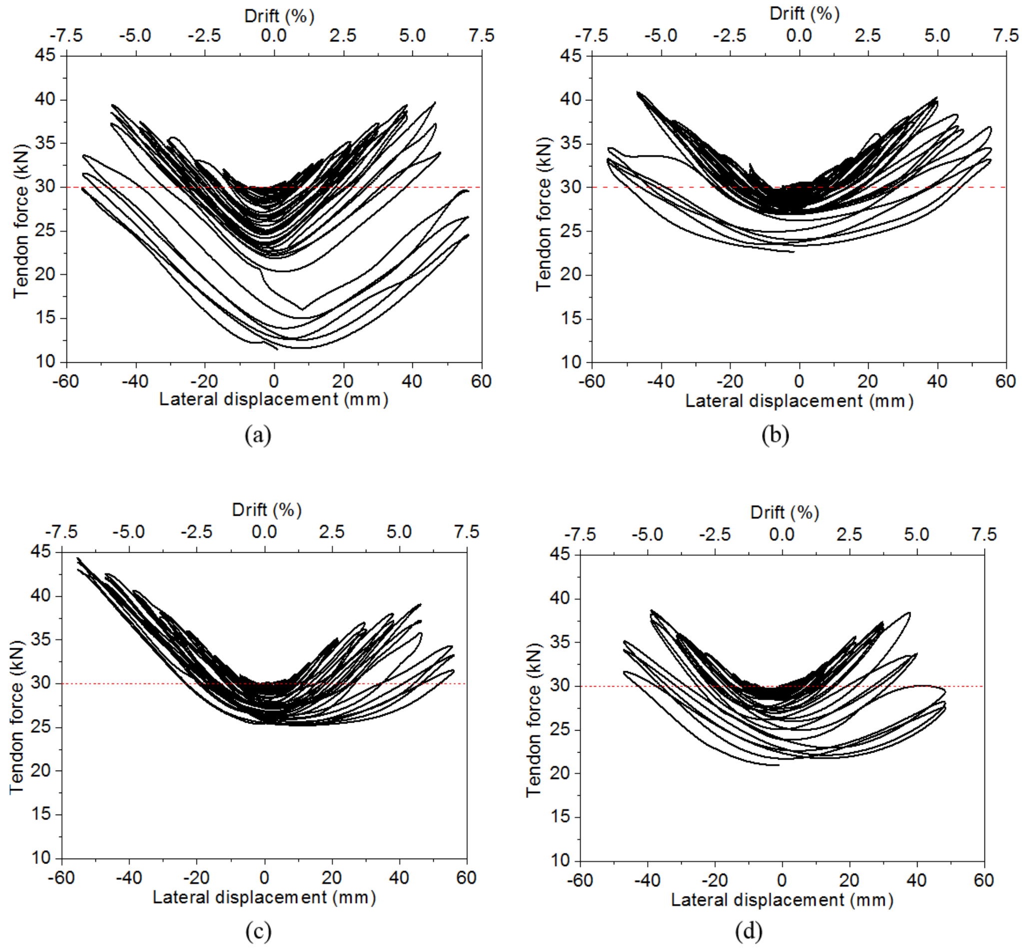



Fig. 11. Tendon force histories (a) 5seg, (b) 5segED, (c) 7seg, (d) 7segkey

## 3.4 Cumulative energy dissipation

For a structure under earthquake loading, energy absorption capacity is an important property. The energy dissipated by the column is derived by calculating the area covered by the hysteretic loops. Fig. 12 shows the cumulative energy dissipation of the tested columns in this study. Among all the specimens, when the drift ratio was lower than 5%, the monolithic column dissipated more energy than the segmental columns owing to large plastic deformations. By adding ED bars across the column joints, column 5segED dissipated 626kN.mm of energy at 5% drift ratio, which was 39% higher than that of column 5seg without ED bars. As the drift ratio further increased, more energy was dissipated by the segmental column with ED bars. By comparing column 5seg and 7seg, it was found that before 6% drift, the cumulative energy dissipated by column 7seg was higher than column 5seg. This is because that the base segment of 7seg experienced more damage than column 5seg and also more joint opening and slippage. After 6% drift, more energy was dissipated by column 5seg. This might be caused by development of cracks in the segments of 5seg and significant loss of prestressing force owing to the concrete damage at the anchorage zone in column 5seg after 6% drift. For the column 7segkey, the energy dissipation increased remarkably after 4% drift. This is because that the bottom two segments of this column experienced serious damage during the test.

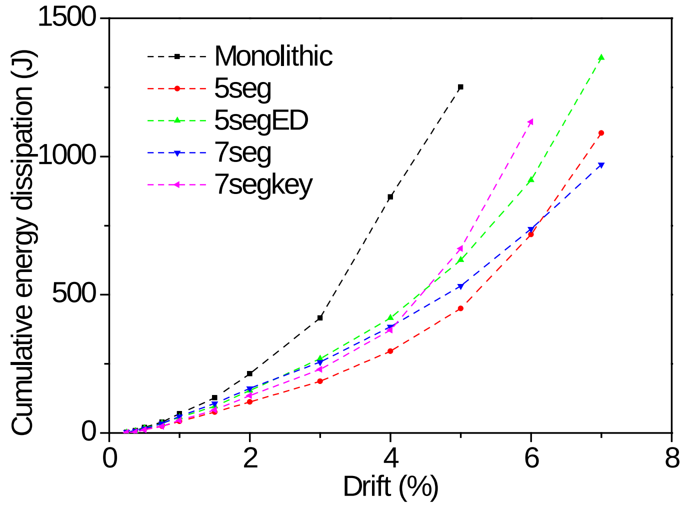



Fig. 12 Cumulative energy dissipation of the columns

## 4. Conclusions

In this paper, the performance of segmental columns under cyclic loading was investigated. One monolithic column and four segmental columns were tested. The response of each column including the damage pattern, hysteretic curve and energy dissipation was analyzed. Different designs such as adding ED bars, number of segments and concrete shear keys were studied to examine the influences of different designs on their seismic performance. The test results showed that the damage of segmental columns was concrete crush around the joints, while for the monolithic column the damage was flexural cracks, crushing of concrete, and also fracture of longitudinal reinforcement bars. All the segmental columns showed much better ductility. They were able to achieve 5% drift level without significant decrease in lateral strength while the strength of monolithic column started to drop significantly after 2% drift ratio. Owing to the prestress tendon, segmental columns had much smaller residual drifts than that of the monolithic column at the same drift. The ED bars could increase the energy dissipation of the segmental column obviously. Concrete shear keys could prevent the slip between the segments. However, severe damage could occur due to stress concentration around the shear keys. Modified designs of shear keys need to be developed to minimize the stress concentration of segmental column with shear keys to resist possible large lateral shear force. From the test results of column 5seg and 7seg, the segmental column with five segments and seven segments had similar seismic performance. During the test loss of prestressing force was found. Since the prestressing force directly affect the column strength, carefully design of the prestressing force and anchorage of the tendon should be made to avoid loss of large amount of prestressing force.

## 5. Acknowledgements

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