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ANALYSIS OF PRECAST SEGMENTAL CONCRETE COLUMNS WITH UNBONDED POST-TENSIONED TENDONS UNDER CYCLIC LOADING

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Abstract

Prefabrication of buildings and bridges are becoming more and more popular in construction industry. Precast segmental column has been proposed to accelerate construction speed. In the precast segmental column system, segments are precast and then clamped together by bonded or unbonded tendons. For application of precast segmental columns in prefabricated structures in seismic regions, many experimental studies on the performance of precast segmental columns under cyclic loadings have been reported. Owing to the complexity in modelling such structures under dynamic loading, numerical study of precast segmental columns subjected to dynamic loads is limited. In this study, a three-dimensional finite element model for precast segmental column with unbonded tendon at the center of the column is built to predict the responses of such columns under seismic loadings. The model is first validated against the cyclic test results and then used to perform parametric studies to investigate the influence of two parameters on the performances of the precast segmental column. The first parameter is the energy dissipation (ED) bar ratio and the second one is the prestressing force. Numerical simulations of segmental columns with different ED bar ratios and prestressing forces subjected to cyclic loadings are carried out. It is found that by increasing the ED bar ratio, the energy dissipation of the system increases significantly. However, the residual drift also increases with the ED bar ratio. Prestressing force is also important for segmental columns. The ultimate strength of the column could be increased by increasing the prestressing force, but increasing the prestressing force in the tendon also increases initial stress in the concrete which causes more damage to the concrete segments. The validated numerical model in this study can be also used in future studies to predict seismic responses of segmental columns.

Keywords: Segmental column; seismic performance; numerical modelling; unbonded post-tensioned tendon

1. Introduction

In recent years, prefabricated buildings and bridges have become more and more popular in construction industry around the world. In comparison with cast-in-place construction, the precast system has a lot of advantages. For example, since most of the components of the structure are cast and cured in factories, the onsite construction time can be reduced significantly. As a result, the traffic disruption can be also minimized. In addition, the quality of the structure and safety for workers can be also improved. Due to these innate advantages, it is a promising structure system in construction industry that can significantly improve the construction efficiency. Precast segmental column is one of the prefabricated structures, which has been proposed to expedite bridge and building constructions. Despite its numerous advantages, its applications are still limited to areas of low seismicity due to insufficient knowledge about its performance under seismic loading. A lot of research has been carried out to study the seismic behavior of precast segmental columns recently [1-8]. However, most of these studies are experimental based. Owing to the complexity, numerical modelling of precast segmental column subjected to dynamic loading is limited.

In the precast segmental column system, segments are prefabricated and then clamped together by post-tensioned tendons. The segments rock between each other under seismic loading and return back to their initial location due to the restoring force provided by the tendons. As a result, precast segmental column has a better self-centering ability in comparison with monolithic columns. However, previous studies found that precast segmental columns with only prestress tendons across the segment joints showed unsatisfactory energy dissipation capability [9]. In order to increase the energy dissipation capacity of the segmental columns, different energy dissipation systems have been proposed, including internal energy dissipation (ED) bars and external energy dissipation devices [3, 9-11]. According to these previous studies, the use of ED systems increased the energy dissipation of the columns, but also increased the residual displacement. Optimized ED bar ratio which increases column energy dissipation capacity but also keeps the residual displacement of the column within acceptable range needs to be investigated.

Prestressing force is another important factor that affects the performance of segmental column. Ou et al. tested four precast segmental columns [9]. One of the columns was loaded with a posttensioning force of 1042kN, another one was applied with 312kN posttensioning force. The test results showed that by increasing the posttensioning force, the ultimate strength of the column could be increased. Also, the residual drift was reduced with the increase of the posttensioning force. However, increasing the posttensioning force also increased the axial compression stress in the concrete of the whole column. Higher initial axial compression stress in the concrete may result in early failure of the column which will reduce the ductility of the column.

Several numerical analyses on precast segmental columns have been carried out by previous researchers [12-16]. Nikbakht et al. used ANSYS to simulate the performance of segmental column [12]. Ou et al. developed a numerical model in ABAQUS [16]. Dawood et al. also used ABAQUS to model the backbone curve of the segmental column under cyclic loading. To systematically investigate the influences of energy dissipation (ED) bar ratio and the prestressing force level on the performance of the segmental column, in this paper, a three-dimensional finite element model of the segmental column was developed by using ABAQUS. The numerical model was validated with an existing experimental test in terms of the damage pattern, hysteretic curve, and increase of tendon strain. The validated model was then used for parametric studies to investigate the influence of energy dissipation bars and prestressing force on the performance of segmental column under cyclic loading. Modelling methods and details of the numerical models which could be useful for future design and analysis of segmental columns were provided in this paper.

2. Numerical modelling

2.1 Model description

In this study the numerical model was developed and calibrated based on the experimental test performed by Hewes and Priestley [1]. The column (JH1) had four precast concrete segments connected with a prestress tendon at the centre of the column. The base segment had a height of 610mm and the upper three segments were

914mm in height. The segments had a circular cross section with a diameter of 610mm. The base segment was strengthened by a steel jacket with a thickness of 6mm. The upper three segments were transversely confined by spiral reinforcement with a diameter of 9.5mm and spacing of 75mm. Eight longitudinal steel bars with a diameter of 12.7mm were placed around the section evenly. No steel bars were put in the base segment since it was confined with the steel jacket. The tendons used in this column were ASTM A779 Grade 270 prestressing strands. The total cross-sectional area of the tendons was 2665mm^2. The design details and material properties were shown in Fig. 1 and Table 1, respectively.

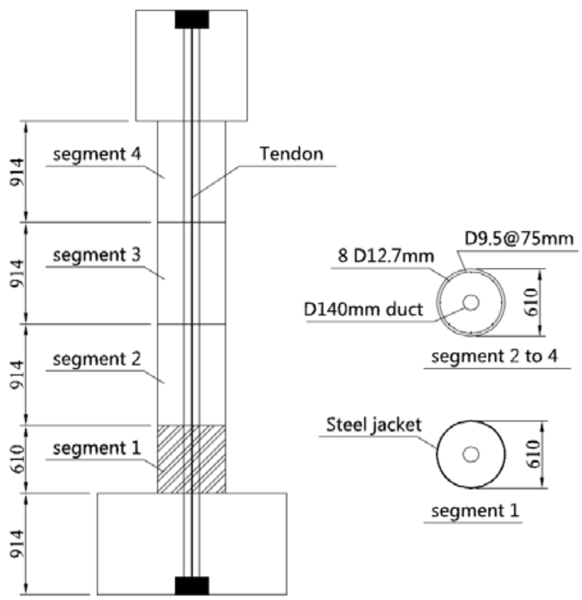


Fig. 1 Design details of the specimen

Table 1 Material properties of the specimen

Item	No. and Size (mm)	f_c' or f_y (MPa)
Concrete	-	41.4
Longitudinal bars	8D12.7	410
Transverse bars	D9.5@75	410
Steel jacket	6mm thick	317
Tendons	27D12.7	1860

2.2 Finite element model

A three-dimensional finite element model of the above segmental column was built using ABAQUS/Standard [17]. The concrete column segments, footing, and top mass were modelled with 3D brick elements (C3D8R). Three models are provided in ABAQUS to model concrete, including smeared crack model, brittle cracking model and concrete damage plasticity model. The damaged plasticity model was chosen since it was the most suitable model for modelling reinforced concrete structures subjected to cyclic and dynamic loading in

ABAQUS [17]. For the concrete material, the concrete model develop by Mander et al. [18] was adopted for the stirrup confined concrete and the model from Han et al. [19] was used for the steel tube confined concrete. Truss element (T3D2) was used to model the steel reinforcements including the longitudinal and transverse mild reinforcements. The reinforcements were embedded in the concrete. The steel tube was modelled with shell element (S4R).

The joints of segmental column normally experience openings under lateral cyclic loading. In order to model such behavior, surface to surface contact elements were adopted. Shear behavior between the master and slave surface was modelled by tangential friction. The assumed friction coefficient was 0.5 as recommended by previous researchers [13]. The normal contact behavior between the surfaces was modelled by hard contact. Thus the surfaces were allowed to separate without any tensile resistance and also able to develop compression when the surfaces were in contact. Similarly, the contact between the unbonded post tensioning tendon and the duct in the concrete was modelled with surface-to-surface contact. No friction was assumed between the tendon and the duct.

To simulate the fixed footing, the nodes of the bottom surface of the footing were totally constrained. For the anchorage of the tendon, two ends of the tendon were embedded in the surrounding concrete. The loadings included axial load, lateral cyclic load and the prestressing force of the tendon. Three loading steps were defined. In the first step, the prestressing force was modelled by initial stress condition and imposed to the tendon. In the second step, the axial load was modelled as a surface pressure and loaded on the top surface of the mass block. In the third step, the lateral displacement control cyclic loading was imposed to the top mass with predetermined displacement. The cyclic loading history is shown in Fig. 2. The finite element model is shown in Fig. 3.

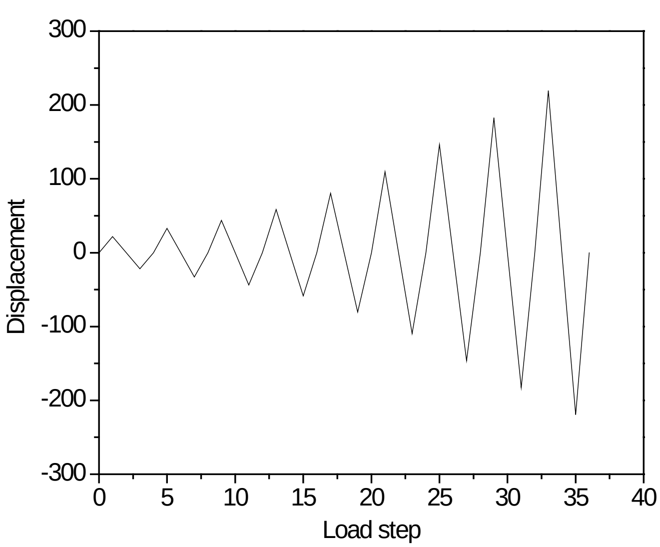


Fig. 2 Cyclic loading history

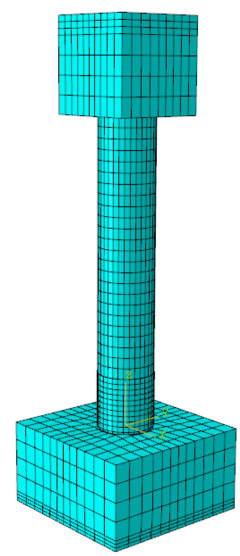


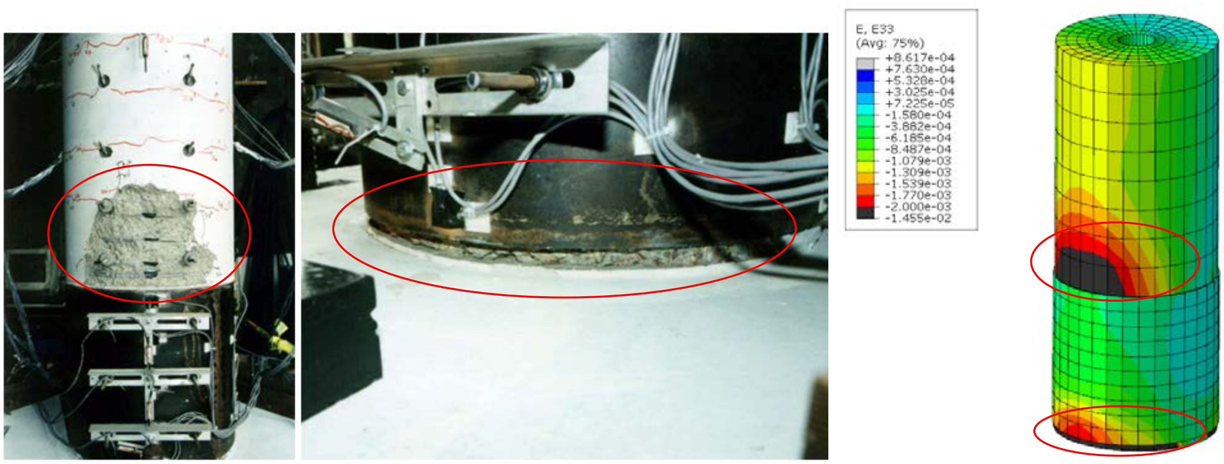
Fig. 3 The FE model

3. Model validation

The simulated results of the numerical model are compared with the experimental results in terms of damage mode, lateral force-displacement relationship and strain increase of the tendon. Fig. 4 shows the damage mode of the column from the test result and the numerical model at 3% drift ratio. Fig. 4 (a) shows the damage of the column during the experiment. Fig. 4 (b) shows the axial strain of the column. During the test, the cover concrete of segment two spalled at 3% drift level. From the numerical results, it is also observed that large strain occurred at the toe of the second segment. The dark area of the second segment in Fig. 4 (b) shows the concrete elements with high axial strain. At the joint between the footing and the base segment, concrete crush was observed in the test. Large strain is also found in the numerical model. The numerical model is able to capture the damage mode of the tested segmental column.

Fig. 5 shows a comparison of the hysteretic curves of the numerical model and the experimental results. Good agreement can be observed between these two curves. It should be noted that at the tip of the hysteretic curve, the lateral force of the test results degraded vertically which could be possibly explained that when the column reached the maximum displacement at each drift level, the column was held for taking photos and damage inspection. As a result, the strength of the column degraded while the displacement remained the same. Another point is that the residual drift of the column is underestimated by the numerical model. The reason may be that the concrete model of the numerical simulation could not precisely model the damage of the concrete. Table 2 summarizes the predicted value and errors of the lateral loading capacity at each drift level. It can be found that the numerical model is able to predict the experimental force-displacement response of the unbonded segmental column with good precision.

The tendon strain increase of the test result and the modelling result is also compared. As shown in Fig. 6, for the test result only the maximum strain increase at each drift level is given while for the numerical results the history of the strain increase is obtained from the numerical model. It can be observed that the numerical results of the tendon strain increase at each drift ratio agrees well with that of the experimental results.



(a) (b)

Fig. 4 Comparison of damage pattern: (a) Damage pattern in the test; (b) Axial strain of the numerical model

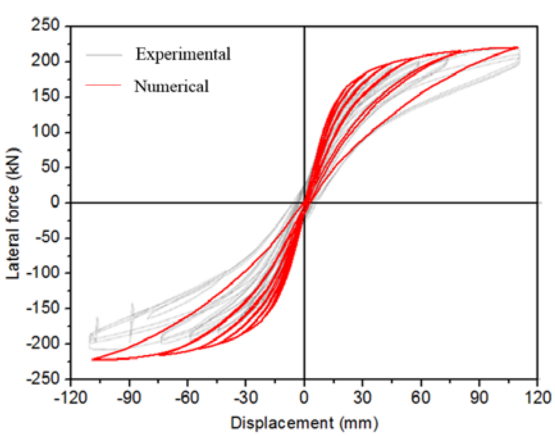


Fig. 5 Comparison of the hysteretic curves

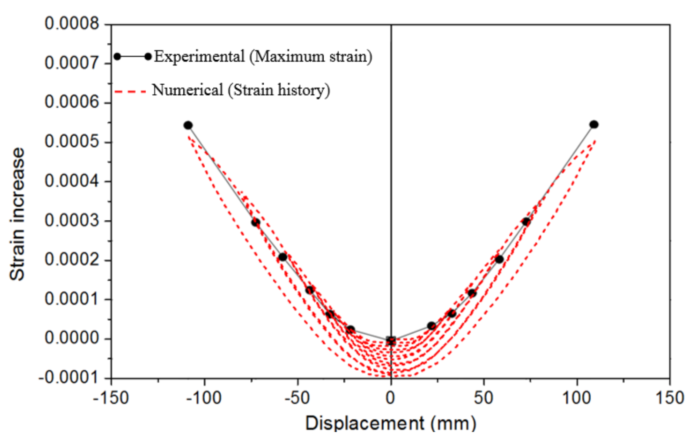


Fig. 6 Comparison of tendon strain increase

Table 2 Comparisons of numerical predicted and experimental obtained lateral force at each drift level

Drift (%)	Experimental	Numerical	Error (%)
0.6	164.7	161.5	2.0
-0.6	-156.2	-164.6	5.3
0.9	186.7	184.1	1.4
-0.9	-175.6	-186.4	6.1
1.2	196.9	197.2	0.1
-1.2	-185.3	-198.6	7.2
1.6	206.1	205.9	0.1
-1.6	-194.9	-206.7	6.0
2	210.4	215.4	2.4
-2	-199.4	-216.2	8.4
3	217	220.3	1.5
-3	-206.3	-222.2	7.7

4. Parametric study

The above calibration study verified the accuracy of the numerical model, which is used here to perform parametric simulations to investigate the influences of the ED bar ratio and prestressing force level on responses of segmental columns subjected to cyclic loadings. Without loss of generality, the above tested segmental column is adopted here as the reference column. New numerical models are developed by adjusting the ED bar ratios and the prestressing force levels of the reference column.

4.1 Influence of ED bars

As reviewed above, previous experimental and numerical studies revealed that segmental columns connected only with prestress tendons had limited energy dissipation ability. Thus, to increase the energy dissipation ability of the segmental column, eight mild steel bars were added to the reference column across the joint between the base segment and the footing as well as the joint between the base segment and the second segment in the modified numerical model. The specimens were named as E1-E5, in which E1 is the reference column JH1. The other four specimens E2-E5 are modified columns with mild steel bars of diameter 10mm, 16mm, 20mm and 24mm respectively. The corresponding ED bars ratios are 0.23%, 0.58%, 0.91% and 1.31%.

Fig. 7 (a) shows the hysteretic curves of the five columns with different ED bars ratios. To better observe the influence of ED bars, the hysteretic curves of E1 and E5 are plotted in Fig. 7 (b). It can be found that by increasing the ED bars ratio, the maximum lateral strength of the column increases. For the original column E1 without ED bar, the maximum strength capacity is about 220.3kN while for the column E5 with 1.31% ED bars ratio the maximum strength reaches to 302.4kN. Also, the area of the hysteretic curve becomes larger with the increase of the ED bars ratio, indicating larger energy dissipation capacity. The cumulative energy dissipated by each specimen is shown in Fig. 8. It can be observed that the ED bars greatly increases the energy dissipation capacity of the segmental column. The cumulative energy dissipated by column E5 with 1.31% ED bars ratio is 60.8kN-m, which is 3.7 times larger than that of the original column E1 without ED bar. Adding ED bars is effective in increasing the energy dissipation of the column. It should be noted that as the ED bar ratio increases the residual drift also increases. This is due to plastic deformation of the ED bars. At 3% drift level, column E1 without ED bar has a residual drift of 0.09% while column E5 with 1.31% ED bar ratio has a residual drift of 0.4%. Table 3 summarizes the ultimate strength, cumulative energy dissipation and residual drift of E1 to E5. It can be observed the column without ED bars dissipates limited energy but shows small residual drift while adding ED bars increases the energy dissipation capacity but also increases the residual drift. These observations are consistent with the experimental results in previous study [9]. As mentioned above, the current numerical model underestimates the residual drift as compared with that of the tested column. More experimental studies are needed to determine an appropriate ED bar ratio which compromises the column energy dissipation capacity and the residual drift.

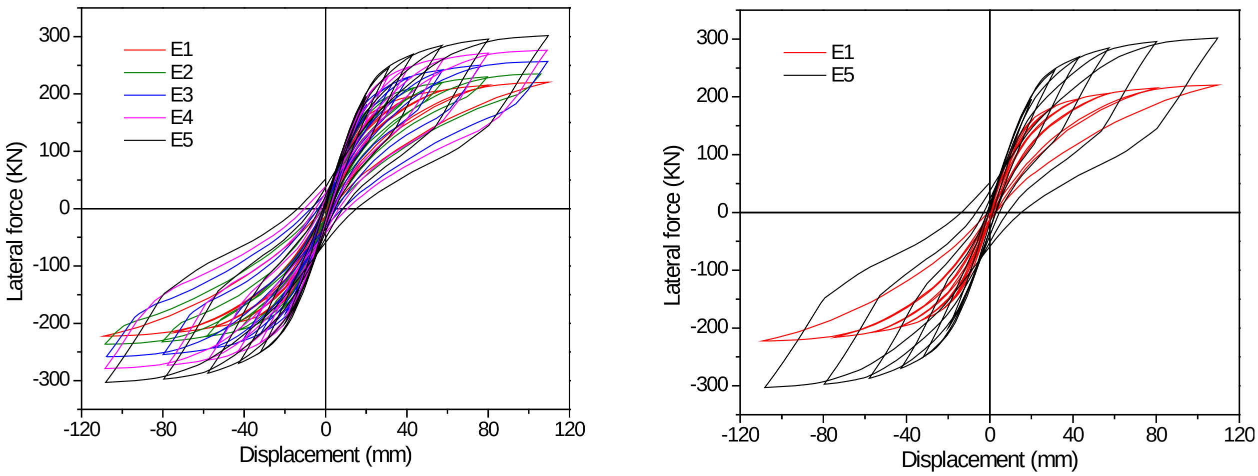


Fig. 7 Comparison of hysteretic curves: (a) E1 to E5; (b) E1 and E5

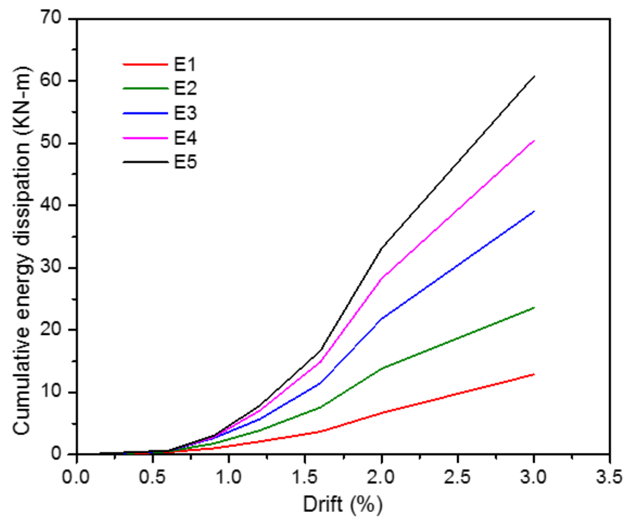


Fig. 8 Cumulative energy dissipation capacity of E1 to E5

Table 3 Summary of modelling results of E1 to E5

Column	Ultimate strength (kN)	Cumulative energy (kN-m)	Residual drift (%)
E1	220.3	12.9	0.09
E2	235.5	23.6	0.12
E3	256.5	39.0	0.24
E4	277.2	50.4	0.30
E5	302.2	60.8	0.42

4.2 Influence of prestressing force

The prestressing force level is another important factor that affects the performance of the segmental column. When the column deforms under seismic loading the posttensioned tendons will be elongated, the lateral component of the prestressing force and the moment induced by the tendon elongation and segment compression provide the lateral resistance for the column. After removing the lateral load, the prestress tendon also helps to pull the column back to its original position. To investigate the influence of posttensioned force on the performance of the segmental column, three specimens with different initial prestressing force are simulated. This group of specimen P1, P2 and P3 has initial prestressing force of 2230kN, 3120kN and 4030kN, respectively. Fig. 9 shows the force-displacement relationship of the specimens under different initial prestressing force level. It can be observed that the column P1, P2 and P3 show the maximum strength at 3% drift ratio of 220.3kN, 260.5kN and 296.9kN. By increasing the initial prestressing force, the lateral strength of the column increases. Similar result was observed in previous study [9]. Fig. 10 shows the cumulative energy dissipation capacity of P1, P2 and P3. At 0.6% drift level, the energy dissipated by the columns is almost the same. This is because that the columns have just started to experience nonlinear behaviour and the concrete damage is minor. With the increase of the drift levels, more damage is accumulated in the concrete and thus the cumulative energy dissipation of the column increases. The energy dissipated by the column increases with the increase of the prestressing force. However, higher initial prestressing force means higher initial axial stress in the concrete, more damage and cracks are formed in the concrete as the drift ratio increases, leading to more energy dissipation.

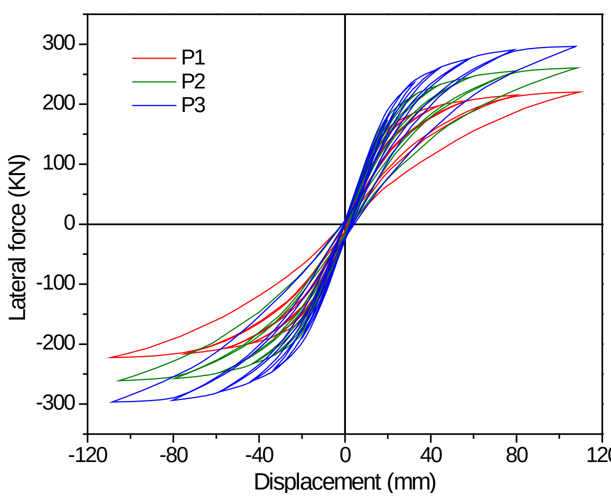


Fig. 9 Hysteretic curves of P1, P2 and P3

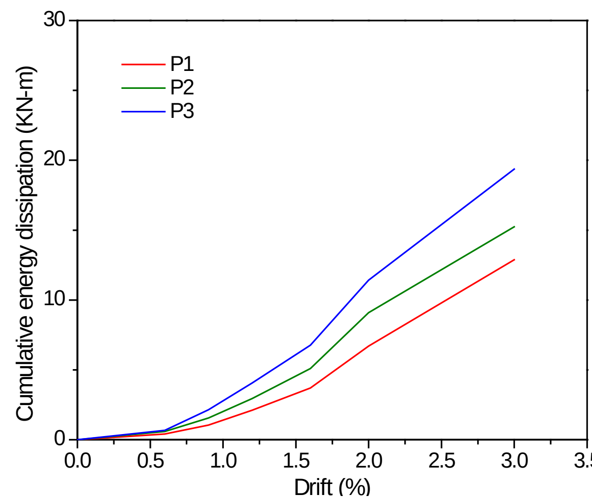


Fig. 10 Cumulative energy dissipation capacity of P1, P2 and P3

5. Conclusions

In this paper, a detailed 3D numerical model was developed to investigate the cyclic performance of precast segmental columns with unbonded posttensioned tendons by using ABAQUS/Standard program. The model was first validated against the experimental results and then the validated numerical model was used to investigate the influences of energy dissipation bars and the prestressing force on the performance of segmental columns. The modelling results agree well with the experimental results in terms of damage pattern, hysteretic curve and tendon strain increase, indicating the accuracy of the modelling methods. The modelling methods can be used in the future for design and analysis of similar precast segmental columns. It was found that adding mild steel energy dissipation bars across the joint remarkably increased the energy dissipation capacity of the segmental columns. Also, the ED bars increased the lateral strength of the column. However higher ED bar ratio also resulted in larger residual drift due to the plastic deformation of ED bars, thus optimum ED bar ratio needs to be determined for a compromised energy dissipation capacity and acceptable residual drift. Higher initial prestressing force in the tendon resulted in higher lateral strength and higher energy dissipation of the column. However increasing the prestressing force in the tendon also increased initial stress in the concrete which led to more damage to the segments.

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7. References

[1] Hewes JT, Priestley MN (2002): Seismic design and performance of precast concrete segmental bridge columns. *Technical Report* 2002/5 (No. SSRP-2001/25).

[2] Billington SL, Yoon J (2004): Cyclic response of unbonded posttensioned precast columns with ductile fiber-reinforced concrete. *Journal of Bridge Engineering,* 9 (4), 353-63.

[3] Chou CC, Chen YC (2006): Cyclic tests of post-tensioned precast CFT segmental bridge columns with unbonded strands. *Earthquake engineering & structural dynamics,* 35 (2), 159-75.

[4] Shim CS, Chung C-H, Kim HH (2008): Experimental evaluation of seismic performance of precast segmental bridge piers with a circular solid section. *Engineering Structures,* 30 (12), 3782-92.

[5] Ou YC, Tsai MS, Chang KC, Lee GC (2010): Cyclic behavior of precast segmental concrete bridge columns with high performance or conventional steel reinforcing bars as energy dissipation bars. *Earthquake Engineering & Structural Dynamics*, 39 (11), 1181-98.

[6] ElGawady MA, Dawood HM (2012): Analysis of segmental piers consisted of concrete filled FRP tubes. *Engineering Structures*, 38, 142-52.

[7] Sideris P, Aref AJ, Filiatrault A (2014): Quasi-static cyclic testing of a large-scale hybrid sliding-rocking segmental column with slip-dominant joints. *Journal of Bridge Engineering,* 19 (10), 04014036.

[8] Tazarv M, Saiid Saiidi M (2015): Low-Damage Precast Columns for Accelerated Bridge Construction in High Seismic Zones. *Journal of Bridge Engineering*, 04015056.

[9] Ou YC, Wang PH, Tsai MS, Chang KC, Lee GC (2009): Large-scale experimental study of precast segmental unbonded posttensioned concrete bridge columns for seismic regions. *Journal of structural engineering*, 136 (3), 255-64.

[10] Marriott D, Pampanin S, Palermo A (2009): Quasi-static and pseudo-dynamic testing of unbonded post-tensioned rocking bridge piers with external replaceable dissipaters. *Earthquake Engineering & Structural Dynamics,* 38 (3), 331-54.

[11] ElGawady MA, Sha'lan A (2010): Seismic behavior of self-centering precast segmental bridge bents. *Journal of Bridge Engineering*, 16 (3), 328-39.

[12] Nikbakht E, Rashid K, Hejazi F, Osman SA (2015): Application of shape memory alloy bars in self-centring precast segmental columns as seismic resistance. *Structure and Infrastructure Engineering,* 11 (3), 297-309.

[13] Dawood H, ElGawady M, Hewes J (2011): Behavior of segmental precast posttensioned bridge piers under lateral loads. *Journal of Bridge Engineering,* 17 (5), 735-46.

[14] Bu Z, Ding Y, Chen J, Li Y (2012): Investigation of the seismic performance of precast segmental tall bridge columns. *Structural Engineering and Mechanics,* 43 (3), 287-309.

[15] Roh H, Ou Y-C, Kim J, Kim W (2014): Effect of yielding level and post-yielding stiffness ratio of ED bars on seismic performance of PT rocking bridge piers. *Engineering Structures,* 81, 454-63.

[16] Ou YC, Chiewanichakorn M, Aref AJ, Lee GC (2007): Seismic performance of segmental precast unbonded posttensioned concrete bridge columns. *Journal of Structural Engineering*, 133 (11), 1636-47.

[17] Simulia DS (2012): Abaqus 6.12 documentation. *Providence, Rhode Island, US*.

[18] Mander JB, Priestley MJ, Park R (1988): Theoretical stress-strain model for confined concrete. *Journal of structural engineering,* 114 (8), 1804-26.

[19] Han L-H, Yao G-H, Tao Z (2007): Performance of concrete-filled thin-walled steel tubes under pure torsion. *Thin-Walled Structures,* 45 (1), 24-36.