Numerical study on the precast concrete filled steel tubular (CFST) segmental column under biaxial cyclic loadings

Chao Li[1], Hong Hao[2] and Kaiming Bi[3]

1. Corresponding Author. PhD student, Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia. Email: chao.li11@postgrad.curtin.edu.au

2. John Curtin Distinguished Professor, Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia. Email: hong.hao@curtin.edu.au

3. Senior lecturer, Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia. Email: kaiming.bi@curtin.edu.au

Abstract

Prefabricated construction is becoming more and more popular around the world due to its innate advantages such as the reduced construction time, better quality control and less environmental impact. In the precast segmental column system, segments are prefabricated and then clamped with posttensioned tendon in the construction site. Extensive research works have been carried out on the seismic behaviour of segmental columns. Previous studies revealed that the residual displacement of segmental column is much smaller compared with the conventional monolith column after a severe earthquake excitation. On the other hand, it was also widely observed that severe concrete spalling damage could occur at the joints between segments, which may influence the performance of the segmental columns. To avoid the possible spalling, steel tubes can be used to confine the concrete segments. It should be mentioned that most previous studies considered uniaxial loading only. In reality, seismic excitations are not uniaxial due to the nature of earthquake. Investigations on the seismic behaviour of segmental columns under biaxial loadings are very limited. This paper carries out numerical simulations on the seismic behaviour of concrete filled steel tubular (CFST) confined segmental column under biaxial cyclic loadings. The detailed three-dimensional finite element model of the column is developed by using finite element program ABAQUS and is validated by the previous experimental data. The validated model is then used to investigate the seismic behaviour of the column under biaxial cyclic loadings.

Keywords: CFST confined segmental column; numerical simulation; biaxial cyclic loadings.

1. INTRODUCTION

Prefabrication of buildings and bridges has attracted a lot of interests in recent years. The benefits of precast structures include less construction time, minimal site disruption, improved construction quality and less environmental impact. Precast segmental concrete column is one of the prefabricated structures. Although it has a lot of advantages, its applications are still limited to areas of low seismicity due to insufficient knowledge of its performance under earthquake loadings. Many experimental studies have been carried out to study its performance under seismic loadings in recent years (ElGawady and Sha'lan 2010, Hewes and Priestley 2002, Kim et al. 2015, Ou et al. 2009, Wang et al. 2008). However, due to the complexity of simulation, numerical studies on the precast segmental column under earthquake loading are limited.

Precast segmental column system is normally constructed by installing the precast segments one by one and then clamping all the segments with post tensioned tendons. During earthquake excitations, the joints between the segments open and close. The rocking behaviour between segments allow the system to dissipate seismic energy and reduce the damage of the whole column (Leitner and Hao 2016). However, due to the rocking behaviour between the segments, the toes of the segments experience excessive compressive stress which causes significant concrete spalling and crushing damage (Shim et al. 2008). To reduce the damage of the concrete, different methods have been proposed including using fibre reinforced concrete (Billington and Yoon 2004), confining the segments with glass fibre tubes (ElGawady et al. 2010) or using steel tube to confine the concrete segments (Chou et al. 2013). Concrete filled steel tubular (CFST) segmental column can be used to reduce the damage since the steel tube increases the compression strength and the ultimate strain of the concrete which in turn improves the ductility of the column. Hewes and Priestley (2002) tested precast segmental columns with the bottom segment confined by steel tube and the test results demonstrated that the steel jacket was effective to reduce the damage of the concrete segments and the column showed good ductility (Hewes and Priestley 2002). Chou and Hsu (2008) investigated the cyclic behaviour of the segmental columns with steel tube confined segments and internal energy dissipation (ED) bars (Chou and Hsu 2008).

Most previous studies on the seismic performance of segmental columns assumed uniaxial lateral cyclic loading. In reality, seismic excitations are not uniaxial due to the nature of earthquake. Limited studies investigated the biaxial performance of monolithic thin wall steel columns (Goto et al. 2006, Goto et al. 2009, Ucak and Tsopelas 2014) and RC columns (Bousias et al. 1995, Chang 2009, Qiu et al. 2002, Rodrigues et al. 2013). No study on investigating the behaviour of segmental column under biaxial lateral cyclic loadings has been reported yet. Moreover, because of the difficulties in numerical modelling of multi-contact surfaces between segments during dynamic responses, most of the studies of segmental column responses to dynamic loadings are experimental based. In this study, detailed numerical simulations are carried out to investigate the seismic behaviour of CFST confined segmental columns under cyclic loadings. The three-dimensional numerical model is firstly validated by the previous experimental results. Then the biaxial performance of the column is investigated based on the validated numerical model.

2. NUMERICAL MODELLING

Detailed three-dimensional model is developed by adopting the finite element code ABAQUS. In this part, the basic information of the column and the detailed modelling methods are presented.

2.1 Model description

The numerical model investigated in this study is developed based on the results of a previous experimental study (Chou and Hsu 2008). The design details of the column are shown in Fig. 1. As shown, the column consists of four concrete filled steel tubular (CFST) segments. The diameter of the column is 500mm and the total height of the specimen is 3720mm. All the segments are confined with steel tube. The thicknesses of the steel tubes for the bottom segments and upper three segments are 5mm and 3mm, respectively. Four energy dissipation (ED) bars with a diameter of 19mm are installed to increase the energy dissipation of the segmental column. The ED bars start from the footing and extend to the top surface of the bottom segment. To avoid stress concentration in the ED bars at the joint interface, a short part (250mm) of the ED bars are left unbonded between the footing and the bottom segment. A bundle of 19 high strength prestress strands is used to clamp the precast segments. The properties of the materials used in the column are shown in Table 1.

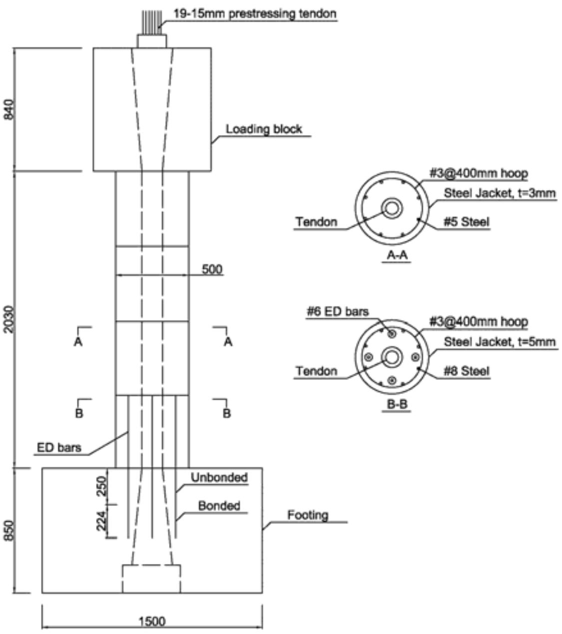

Fig. 1 Design details of the simulated column (Chou et al. 2013)

Table 1. Material properties of the column

Items		Values
Concrete	Strength (MPa)	48
	Poisson’s ratio	0.2
Steel jacket	Thickness (mm)	5mm/3mm
	Elastic modulus Es (GPa)	206
	Yielding stress (MPa)	240/269
	Poisson’s ratio	0.3
ED bars	Diameter	D19
	Elastic modulus Es (GPa)	206
	Yielding stress (MPa)	307
	Poisson’s ratio	0.3
Tendons	Area (mm^2)	2611
	Elastic modulus Es (GPa)	196
	Ultimate stress (MPa)	1860
	Poisson’s ratio	0.3
	Applied PT force (kN)	2321

2.2 Finite element model

The numerical model is developed by ABAQUS/Standard (Simulia 2012). The precast concrete segments, prestressing tendon, footing, and loading block are modelled with C3D8R brick elements. The model developed by Han et al. (2007) is used to simulate the nonlinear behaviour of the steel tube confined concrete. The reinforcements, including the longitudinal reinforcements, transverse reinforcements and ED bars are modelled with T3D2 truss elements. Bilinear elastic-plastic model is used for the steel reinforcements. Surface to surface contact elements are used to model the joints between the precast segments. The normal contact between the adjacent surfaces is modelled by hard contact which allows openings and compression between the surfaces. The tangential friction is used to model the tangential behaviour between the contact surfaces and the friction coefficient is assumed to be 0.5 (Dawood et al. 2011). Fig. 2 shows the developed numerical model in this study.

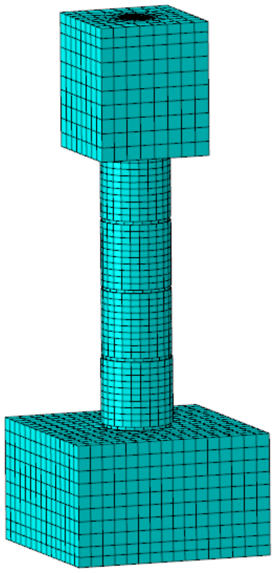

Fig. 2. Numerical model

3. MODEL VALIDATION

Fig. 3 shows the displacement of each loading steps and the loading path for the uniaxial loading. As shown in Fig. 4, the modelling results of the developed numerical model under the uniaxial cyclic loading is compared with the experimenal results. The black solid line represents the experimental results and the red dash line is the results of the numerical model. It can be seen that the modelling results agree well with the testing results. The initial stiffness and the ultimate loading capacity are well captured by the numerical model, indicating the accuracy of the the numerical model developed in this study.

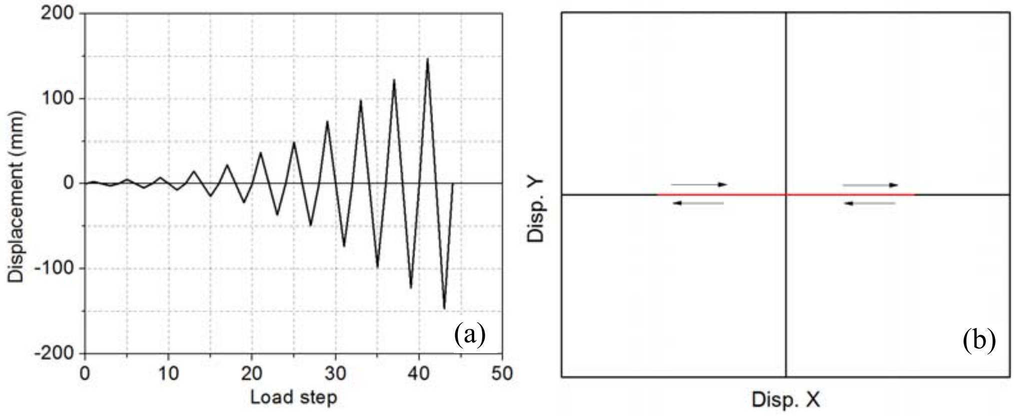

Fig. 3 (a) Uniaxial loading protocol, (b) Uniaxial loading path

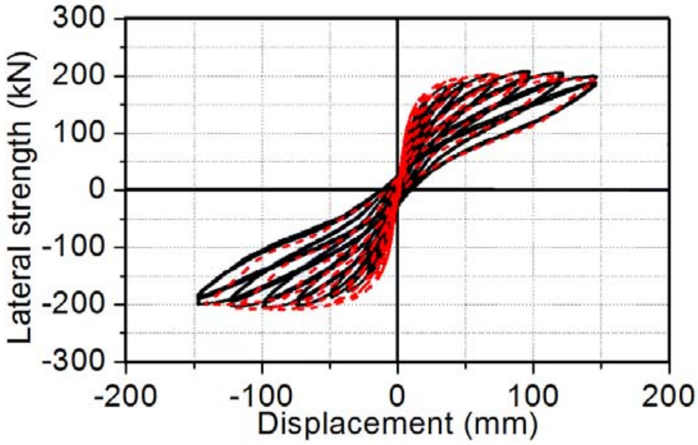

Fig. 4 Comparison of modelling and experimental results

4. INFLUENCE OF BI-DIRECTION LOADING

The validated model is used to investigate the biaxial performance of the segmental column in this section. As shown in Fig. 5 (a) and (b), two biaxial loading paths named as BC1 and BC2 are investigated. The displacement amplitudes for each direction of the biaxial loadings are the same with the uniaxial loading (Fig. 3 (a)).

Fig. 6 shows the comparison of the hysteretic curves between the column under uniaxial loading and biaxial loading paths. It can be observed that the initial stiffness is not significantly affected by the biaxial loading. According to Fig. 6 (a-b), the column under the biaxial loading path BC1 shows slight strength degradation and residual displacement increment compared to the results of the column under uniaxial loading. This observation indicates that the column experiences insignificant coupling effects under the biaxial loading path BC1. The reason is that the loadings in X and Y directions increase separately and have no relations with each other. On the other hand, for the column under the biaxial loading path BC2, as shown in Fig. 6 (c-d), more significant strength degradation and residual displacement increment can be found. This is because the displacements in X and Y directions of the BC2 are coupled with each other, causing more significant plastic deformations and damage in both directions. The plastic deformations and damage include the damage of the concrete, the plastic deformation of the steel tube and the plastic deformation of the ED bars. These damages are observed in the column under both uniaxial and biaxial loading, but the damages are more serious in the column under biaxial loading, resulting strength degradation and residual displacement increase. Therefore, the response of the segmental column under biaxial loading is different from that of the column under uniaxial loading and it is also highly dependent on the types of the biaxial loading paths.

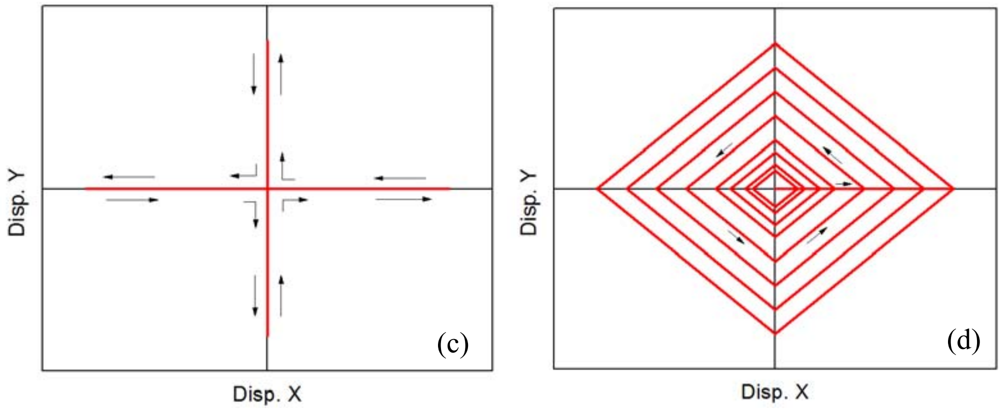

Fig. 5. (a) Biaxial loading path-BC1, (b) Biaxial loading path-BC2

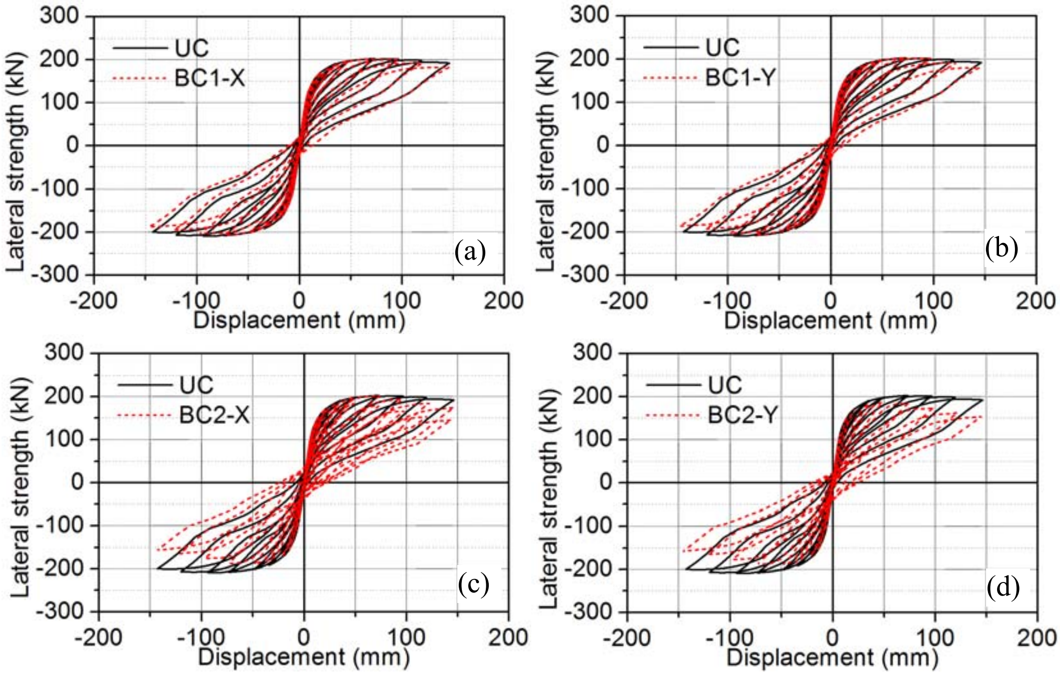

Fig. 6 Comparisons of the hysteretic curves

5. CONCLUSIONS

This study carries out numerical simulations on the CFST confined segmental columns under biaxial cyclic loadings. The detailed three-dimensional finite element model of the column is developed and validated based on a previous experimental study. Numerical results show that the biaxial behaviour of the column is significantly influenced by the loading protocols. In particular, under the biaxial loading protocol BC1, the column shows slightly strength degradation and residual displacement increment compared to the uniaxial loading protocol. However, for the biaxial loading protocol BC2, significant strength degradation and residual displacement increment are observed. The results demonstrate the necessity of considering the bi-directional ground motions simultaneously in predicting structural responses to earthquake motions.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the finacial support from ARC. The first author also wants to acknowledge the scholarship from China Scholarship Council.

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