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Load Capacity and Failure Modes of Axially and Eccentrically Loaded Thin-Walled Steel Tubular Slender Columns Filled with Concrete

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ABSTRACT: The purpose of this paper is to investigate the load capacity and failure modes of thin-walled steel tubular slender columns filled with concrete under axial and eccentric loads. Different concrete compressive strengths and length/diameter (width) ratios are adopted for the slender columns. The columns are modelled and analysed by the use of the finite element software ABAQUS. The verification study of the three-dimensional nonlinear finite element modelling is carried out using its corresponding experimental test result. In order to establish the verification of the modelling, all specifications of the experimentally tested column are taken into account in the modelling. Comparing obtained results from the modelling and test uncovers that they agree well with each other. Thus, the accuracy of the modelling is demonstrated. Then, the same modelling method is utilised for modelling and analysing developed slender columns. Variables used for the columns include different load eccentricities, cross-sectional shapes, and steel tube thicknesses. Effects of these variables on the load capacity of the columns are examined. It is concluded that increasing the load eccentricity reduces the load capacity of the slender columns. The circular columns perform better than the square and rectangular columns. Also, enhancing the steel tube thickness results in larger load capacity of the columns. Columns with the large load capacity are desirable in terms of their structural performance in projects. Meanwhile, various failure modes of the columns are widely evaluated and discussed.

Keywords: Slender Column, Load Capacity, Failure Mode, Thin-Walled, Steel, Concrete.

Abbreviations: CFTWST Column, Concrete-Filled Thin-Walled Steel Tubular Column; NFEA, Nonlinear Finite Element Analysis.

I. INTRODUCTION

Columns are main components of most structures. Thin-walled steel tubular columns filled with concrete, i.e. concrete-filled thin-walled steel tubular (CFTWST) columns, have extensively been employed as dominant compression members in modern structural projects. Thus, research on their load capacity and failure modes can be of great importance. The success of the CFTWST columns has mainly been due to the beneficial composite interaction between their constituent materials as the concrete core and steel tube which has led to high strength, large ductility, and high stiffness, and also convenient construction process and large cost saving.

To date there have been research studies on the response of the CFTWST columns worldwide. Bradford [1] introduced an empirical reduction factor to consider the effect of in-filled concrete prism size and the concrete strength class in order to assess the compressive strength of concrete. Thin-walled steel rectangular hollow section columns filled with concrete were evaluated under long-term sustained loads by Han and Yang [2]. Nonlinear behaviour of concrete-filled high-strength stainless steel stiffened slender square and rectangular tubes was studied by Ellobody [3]. Bahrami *et al.,* [4] analysed and developed concrete-filled steel composite columns with and without stiffeners. Bahrami *et al.*, [5, 6] examined tapered concrete-filled steel composite columns under axial and eccentric loads. The axial compressive performance of square concrete-filled double skin tubular columns with inner circular tubes was addressed by Hassan *et al.,* [7]. Huang *et al.*, [8] presented an experimental study on circular concrete-filled steel tubular columns subjected to preload. Mahgub *et al.*, [9] reported experimental tests on the axial compressive behaviour of self-compacting concrete-filled elliptical steel tube columns. A mathematical model was described by Liang [10] which computed the axial load-deflection performance of high-strength circular double-skin concrete-filled steel tubular slender columns under eccentric loading. Lee *et al.*, [11] experimentally tested rectangular thin-walled concrete-filled steel tubular columns with high-strength steel slender section to assess their axial load-carrying capacity. The behaviour of axially-loaded ultra-high strength concrete-filled steel tube circular columns was numerically evaluated by Song and Xiang [12].

The main focus of this paper is the investigation of the load capacity and failure modes of the CFTWST slender columns subjected to axial and eccentric loads. The finite element software ABAQUS is employed to model and analyse the columns nonlinearly. Comparing the results obtained from the nonlinear finite element analysis (NFEA) and experimental test of the column establishes the verification of the modelling. The developed columns are modelled and analysed using various variables as different load eccentricities, cross-sectional shapes, and steel tube thicknesses. Effects of these variables on the load capacity of the columns are examined. Failure modes of the columns are presented and discussed.

II. RESEARCH METHODOLOGY

A CFTWST slender column was experimentally tested to achieve its axial capacity [13]. This column was modelled and analysed for conducting the verification study of the nonlinear finite element modelling. With regard to the demonstration of the modelling accuracy, the same method of the modelling was adopted to nonlinearly model and analyse the developed slender columns.

A. Experimental test of slender column

The geometric specifications of the tested column were diameter (*D*), thickness of steel tube (*t*), and length/diameter ratio (*L/D*) which were respectively as 114.3 mm, 3.35 mm, and 10. Tension tests were done in accordance with ASTM A370-07a [14] with I specimens in order to obtain the yielding stress of the perimeter steel tube. The average value of 287.33 MPa was taken for the yielding stress and the corresponding strain was 0.0014. Concrete mixes were made with the available materials. The axial compressive strength of concrete was determined by tests using 10 cm × 20 cm cylindrical specimens at 28 days. In the same day the column was also tested. The concrete compressive strength was resulted as 88.8 MPa. The test of the column was conducted employing an Instron 8506 servo hydraulic actuator with electronic displacement control. The concentric load was applied on the entire section of the column in the test. Fig. 1 shows the setup of the experimental test of the slender column.

B. Verification study of modelling slender column

In the verification study of the modelling, the tested column was completely modelled using ABAQUS. All the pre-mentioned characteristics of the tested column were considered in the modelling here. The steel material was modelled by the use of a bilinear steel material model including progressive hardening behaviour and softening effects [15]. However, modelling the constitutive behaviour of the concrete material was performed utilising a concrete damage plasticity model [16, 17]. Since concrete was greatly influenced by the confinement effect of the steel tube, its behaviour was different from other common models. The ratio of the second stress invariants on the tensile and compressive meridians was adopted as 0.667. The Poisson's ratios of the concrete core and steel tube were considered as 0.2 and 0.3, respectively.

The solid element C3D8R and the shell element S4R were employed to respectively model the concrete core and steel tube. The contact surface between the concrete core and perimeter steel tube was modelled using the Embedded Region constraint. The friction coefficient of 0.3 was utilised for the contact. A convergence study was carried out on the mesh size of the column to find the most suitable size. As a result, the mesh size of 15 mm was adopted for the column which could lead to the exact result. The displacement method was used to apply the load. When the modelling of the column was absolutely done, it was then analysed nonlinearly.

The load-axial strain curve was achieved from the obtained analysis result. Fig. 2 displays the comparison of the NFEA result with the experimental test result. Since a good agreement existed between the results in terms of their load capacities and behaviours, the modelling was verified. As a consequence, the verified modelling method was followed for modelling the developed columns in the next stage of this research.

Fig. 1. Setup of experimental test of slender column [13].

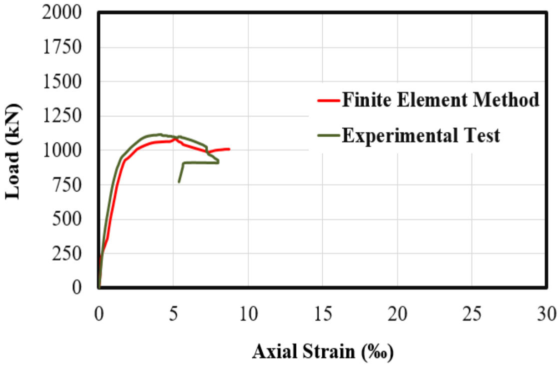


Fig. 2. Verification study of modelling slender column.

C. NFEA of developed slender columns

The development of the slender columns is explained here. Concrete compressive strengths of 32.7 MPa and 88.8 MPa were adopted for the columns. Also, *L/D* (*B*) ratios were taken as 6 and 10. Variables for the columns were load eccentricities (0 mm, 25 mm, and 50 mm), cross-sectional shapes (circular, square, and rectangular), and steel tube thicknesses (2 mm, 3.35

mm, and 5 mm). Considering the above-mentioned features, the developed columns were nonlinearly analysed. A typical model of the developed slender column is illustrated in Fig. 3.

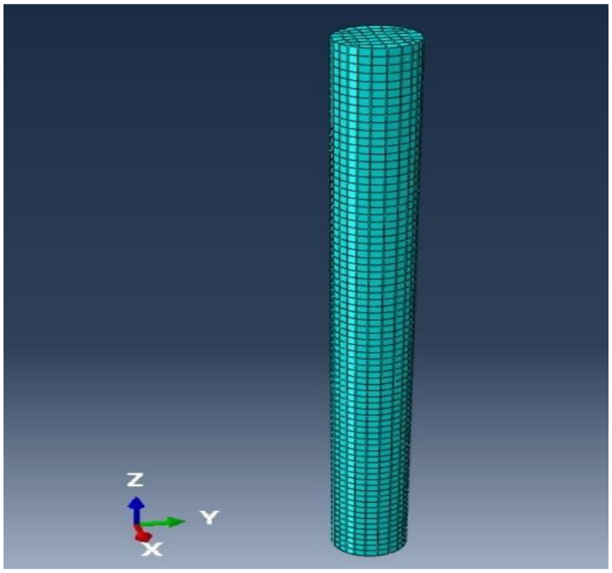


Fig. 3. Typical model of developed slender column.

III. RESULTS AND DISCUSSIONS

The obtained results from the analyses are summarised in Table 1. In the designations of the columns in the table, *C* refers to the columns while the subsequent numbers respectively present the class of the concrete compressive strength, *L/D* (*B*) ratio, eccentricity (*e*), and steel tube thickness (*t*), however, the last letter designates the cross-sectional shape of the slender columns.

Also, load-axial strain curves were plotted from the obtained results under different conditions. Additionally, failure modes were accomplished for the columns. These subjects are represented and discussed below.

A. Effect of load eccentricity on load capacity of slender columns

The achieved load-axial strain curves are depicted in Fig. 4 for the circular slender columns with different load eccentricities, concrete compressive strengths, and *L/D* ratios. However, the steel tube thickness is similar for all the columns. It can be observed from the figure and Table 1 that as the load eccentricity was increased, the load capacities of the columns were reduced. For instance, the increase of load eccentricity from 0 mm (C80-10-0-3.35-C) to 25 mm (C80-10-25-3.35-C) and 50 mm (C80-10-50-3.35-C) resulted in the decrease of the load capacity respectively from 1116 kN to 711 kN and 462 kN, indicating respective reductions of 36.3% and 35%. This point signified the important role of the load eccentricity on the load capacity of the slender columns. Because in the eccentric loads, due to the asymmetry of the loads applied to the column surface, one side of the column was practically subjected to high tensile stresses and the opposite side was subjected to large compressive stresses. These stresses, in turn, caused minor crushing of the concrete core and also yielding of the steel tube owing to the lack of the alignment of the applied load with the direction of the support reaction. Finally, it mitigated the confinement role of the steel tube on the concrete core which led to lower load capacity of the columns.

B. Effect of cross-sectional shape on load capacity of slender columns

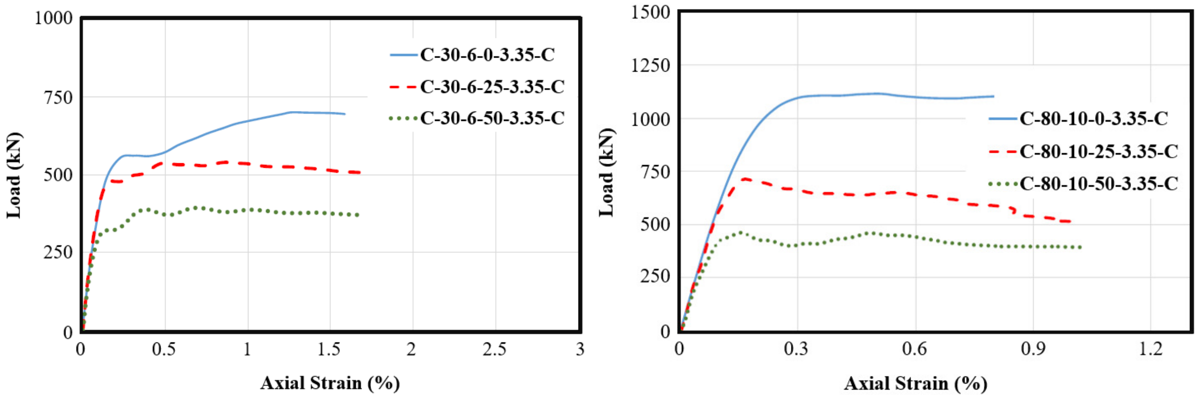
Square and rectangular cross-sections were adopted for the columns in addition to the circular cross-section. The *L/D* ratio of the columns was 10. The same cross-sectional area and materials features of the circular column were also considered for the square and rectangular columns. Fig. 5 presents the load-axial strain curves obtained from the NFEA of the columns. The load capacity of the circular column was 1116 kN which was decreased to 695 kN and 689 kN by the respective applications of the square and rectangular cross-sections. This issue elaborated 37.7% and 38.3% reductions of the load capacity of the circular column by using the square and rectangular cross-sections, respectively. Therefore, a slight difference was witnessed between the obtained load capacities of the square and rectangular columns. Higher load capacity of the circular column than its square and rectangular counterparts was because the steel tube of the square and rectangular columns had flat sides which could not be able to provide the confinement to the concrete core as much as that in the circular column. On the other hand, the whole concrete core was effectively confined in the circular column while the corners of the steel tube in the square and rectangular columns provided more confinement on the concrete core than the flat portions.

C. Effect of steel tube thickness on load capacity of slender columns

Steel tube thicknesses of 2 mm, 3.35 mm, and 5 mm were taken into account for the circular slender columns with different concrete compressive strengths and *L/D* ratios. The comparison of the obtained results from the analyses is demonstrated in Fig. 6. The improvement of the load capacity could be noticed for the columns by the increase of their steel tube thickness. For example, in the case of C30-6-0-2-C with the steel tube thickness of 2 mm the load capacity was 570 kN which was enhanced to 701 kN and 844 kN respectively by the utilisation of C30-6-0-3.35-C with the steel tube thickness of 3.35 mm and C30-6-0-5-C with the steel tube thickness of 5 mm, pointing out the respective enhancements of 23% and 20.4%. Because more confinement was provided on the concrete core by thicker steel tube and the failure of the columns was thus delayed more which resulted in higher load capacity.

Table 1: Specifications of slender columns and obtained load capacities.

No.	Column Label	f'$_c$ (MPa)	L/D (B)	e (mm)	t (mm)	Cross-Sectional Shape	Load Capacity (kN)
1	C-30-6-0-3.35-C	32.7	6	0	3.35	Circular	701
2	C-30-6-25-3.35-C	32.7	6	25	3.35	Circular	540
3	C-30-6-50-3.35-C	32.7	6	50	3.35	Circular	394
4	C-80-10-0-3.35-C	88.8	10	0	3.35	Circular	1116
5	C-80-10-25-3.35-C	88.8	10	25	3.35	Circular	711
6	C-80-10-50-3.35-C	88.8	10	50	3.35	Circular	462
7	C-80-10-0-3.35-S	88.8	10	0	3.35	Square	695
8	C-80-10-0-3.35-R	88.8	10	0	3.35	Rectangular	689
9	C-30-6-0-2-C	32.7	6	0	2	Circular	570
10	C-30-6-0-5-C	32.7	6	0	5	Circular	844
11	C-80-10-0-2-C	88.8	10	0	2	Circular	1007
12	C-80-10-0-5-C	88.8	10	0	5	Circular	1226



(a) *L/D* = 6.

(b) *L/D* = 10.

Fig. 4. Effect of load eccentricity on load capacity of slender columns with different *L/D* ratios.

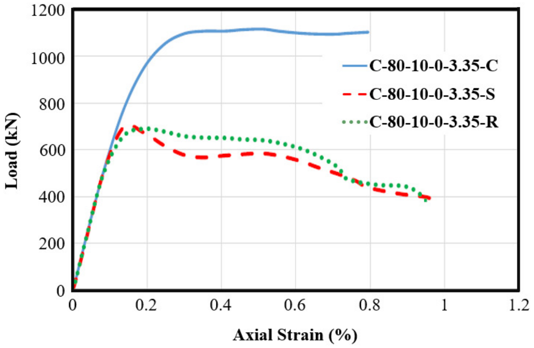
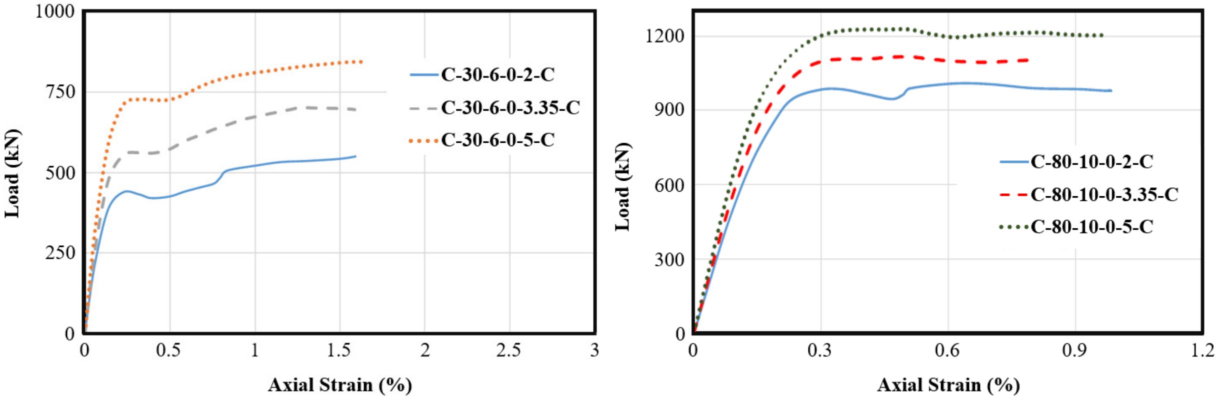


Fig. 5. Effect of cross-sectional shape on load capacity of slender columns.



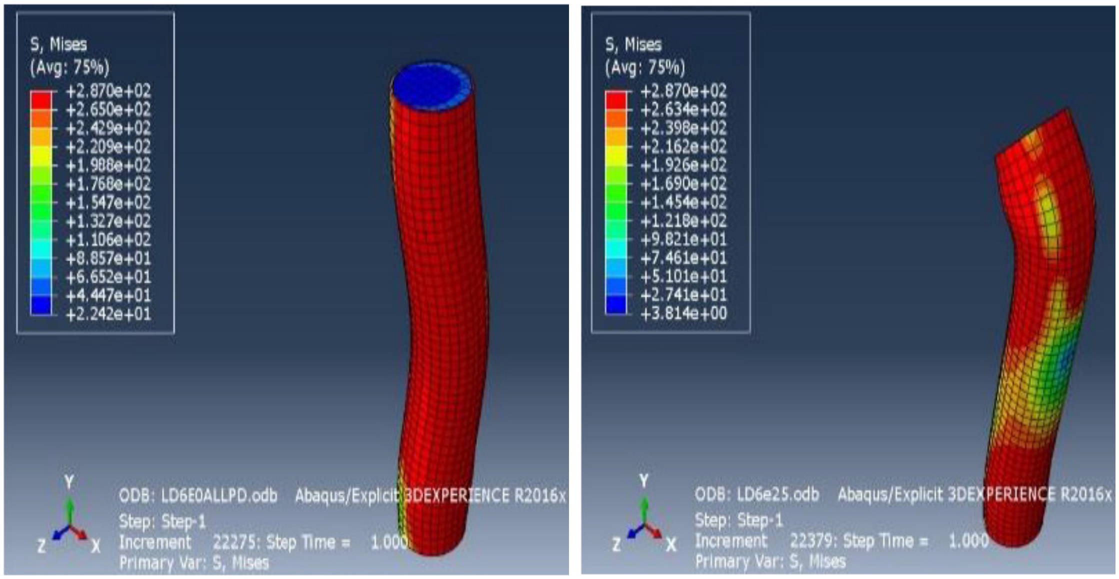
(a) *L/D* = 6.

(b) *L/D* = 10.

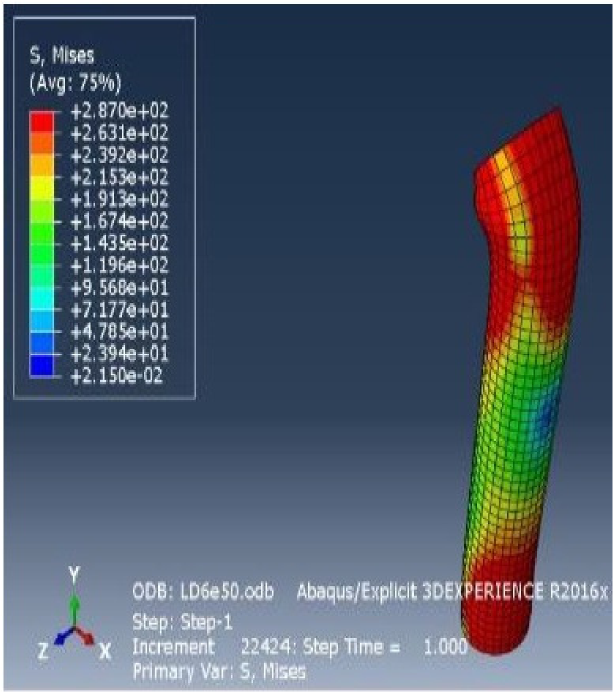
Fig. 6. Effect of steel tube thickness on load capacity of slender columns with different *L/D* ratios.

D. Failure modes of slender columns

Failure modes of the columns are illustrated in Figs. 7-10. As it can be perceived from Figs. 7 and 8, the columns with 0 mm eccentricity exhibited the in-plane displacement and buckling occurred about the mid-height of the columns. However, the columns with the eccentricities of 25 mm and 50 mm showed the out of plane displacement with buckling near the top of the columns. Buckling of the eccentrically loaded columns was larger than the axially loaded columns especially for the columns with *L/D* = 10. Fig. 9 presents the failure modes of the rectangular and square columns. Large buckling was observed about the mid-height of these columns under the axial load, however, their circular counterpart in Fig. 8(a) indicated small buckling. The in-plane displacement and small buckling could be witnessed for the circular columns with different steel tube thicknesses in Fig. 10.

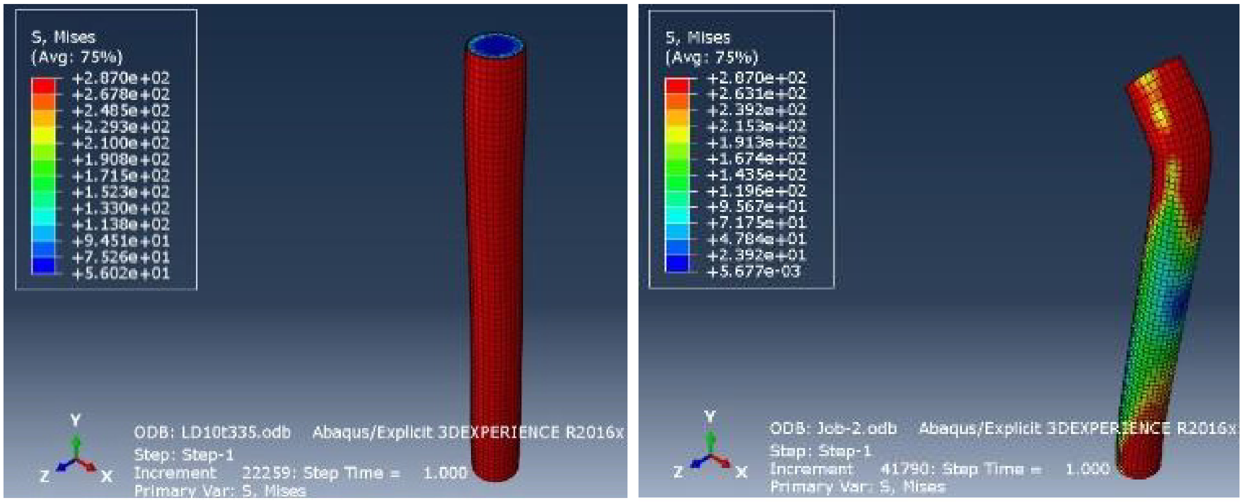


(a) C-30-6-0-3.35-C (b) C-30-6-25-3.35-C

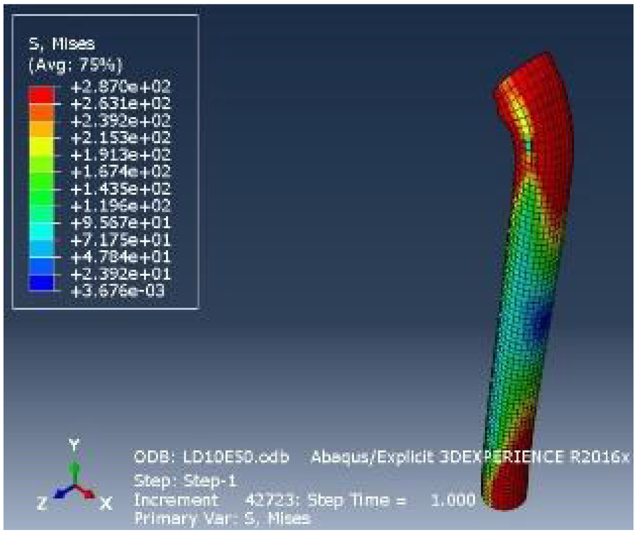


(c) C-30-6-50-3.35-C

Fig. 7. Failure modes of slender columns with *L/D* = 6 under different load eccentricities.

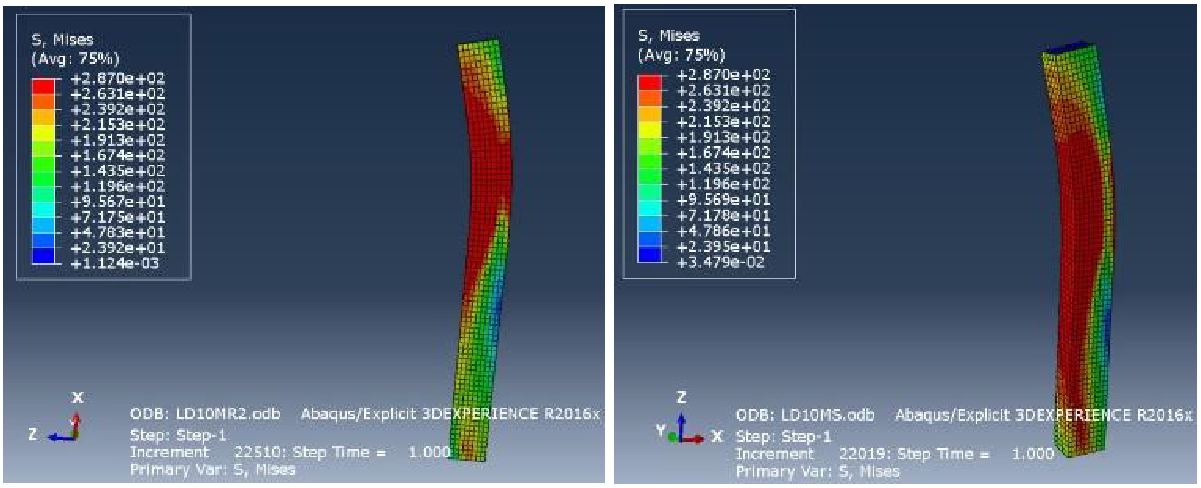


(a) C-80-10-0-3.35-C (b) C-80-10-25-3.35-C



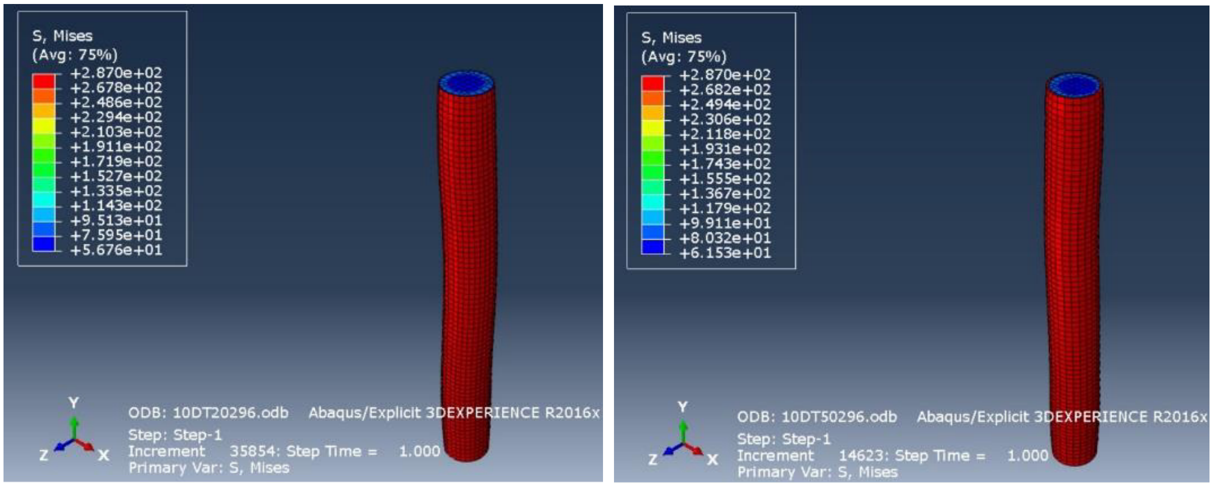
(c) C-80-10-50-3.35-C

Fig. 8. Failure modes of slender columns with *L/D* = 10 under different load eccentricities.



(a) C-80-10-0-3.35-S (b) C-80-10-0-3.35-R

Fig. 9. Failure modes of slender columns with different cross-sectional shapes.



(a) C-80-10-0-2-C (b) C-80-10-0-5-C

Fig. 10. Failure modes of slender columns with different steel tube thicknesses.

IV. CONCLUSIONS

The load capacity and failure modes of axially and eccentrically loaded CFTWST columns were evaluated in this paper. ABAQUS was employed to perform the modelling and NFEA of the columns. The verification of the modelling was established and the developed columns were then modelled and analysed. Different load eccentricities, cross-sectional shapes, and steel tube thicknesses were considered as variables for the columns. It was concluded that the load capacity of the slender columns was decreased by enhancing the load eccentricity. Better performance of the circular columns than their square and rectangular counterparts was achieved. Thicker steel tube resulted in larger confinement effect of the steel tube on the concrete core which finally led to larger load capacity of the slender columns. Failure modes of the columns were widely accomplished. Failure modes of the axially loaded circular slender columns were generally characterised by the in-plane displacement and buckling about the middle of the columns. However, the out of plane displacement and buckling near the top of the columns were seen for the eccentrically loaded circular slender columns. Also, buckling of the axially loaded square and rectangular slender columns was larger than their axially loaded circular counterpart.

V. FUTURE SCOPE

The next step of this study is to assess the energy absorption capacity and stiffness of slender columns under different conditions which can also be important issues to be taken into account from the structural response viewpoint of the columns.

Conflict of Interest. The authors declare no conflict of interest.

REFERENCES

[1]. Bradford, M.A. (1996). Design strength of slender concrete filled rectangular steel tubes. *ACI Structural Journal*, *93*(2): 229-235.

[2]. Han, L.H. and Yang, Y.F. (2003). Analysis of thin-walled steel RHS columns filled with concrete under long-term sustained loads. *Thin-Walled Structures*, *41*(9): 849-870.

[3]. Ellobody, E. (2007). Nonlinear behavior of concrete-filled stainless steel stiffened slender tube columns. *Thin-Walled Structures, 45*(3): 259-273.

[4]. Bahrami, A., Wan Badaruzzaman, W.H. and Osman, S.A. (2011). Nonlinear analysis of concrete-filled steel composite columns subjected to axial loading. *Structural Engineering and Mechanics*, *39*(3): 383-398.

[5]. Bahrami, A., Wan Badaruzzaman, W.H. and Osman, S.A. (2012). Structural behaviour of tapered concrete-filled steel composite (TCFSC) columns subjected to eccentric loading. *Computers and Concrete*, *9*(6): 403-426.

[6]. Bahrami, A., Wan Badaruzzaman, W.H. and Osman, S.A. (2013). Performance of axially loaded tapered concrete-filled steel composite slender columns. *Journal of Civil Engineering and Management*, *19*(5): 705-717.

[7]. Hassanein, M.F., Kharoob, O.F. and Gardner, L. (2015). Behaviour and design of square concrete-filled double skin tubular columns with inner circular tubes. *Engineering Structures*, *100*: 410-424.

[8]. Huang, F., Yu, X., Chen, B. and Li, J. (2016). Study on preloading reduction of ultimate load of circular concrete-filled steel tubular columns. *Thin-Walled Structures*, *98*: 454-464.

[9]. Mahgub, M., Ashour, A., Lam, D. and Dai, X. (2017). Tests of self-compacting concrete filled elliptical steel tube columns. *Thin-Walled Structures*, *110*: 27-34.

[10]. Liang, Q.Q. (2018). Numerical simulation of high strength circular double-skin concrete-filled steel tubular slender columns. *Engineering Structures, 168*: 205-217.

[11]. Lee, H.J., Park, H.G. and Choi, I.R. (2019). Compression loading test for concrete-filled tubular columns with high-strength steel slender section. *Journal of Constructional Steel Research*, *159:* 507-520.

[12]. Song, T.Y. and Xiang, K. (2020). Performance of axially-loaded concrete-filled steel tubular circular columns using ultra-high strength concrete. *Structures*, *24*: 163-176.

[13]. Oliveira, W.L.A., De Nardin, S., El Debs, A.L.H.C. and El Debs, M.K. (2009). Influence of concrete strength

and length/diameter on the axial capacity of CFT columns. *Journal of Constructional Steel Research*, *65*: 2103-2110.

[14]. ASTM A370-07a. (2007). Standard test methods and definitions for mechanical testing of steel products. West Conshohocken, PA.

[15]. Bahrami, A. and Yavari M. (2019). Performance of steel-concrete shear walls with two-sided reinforced concrete. *International Journal of Engineering and Technology Innovation*, *9*(3): 228-239.

[16]. Bahrami, A. and Matinrad. S. (2019). Response of steel beam-to-column bolted connections to blast loading. *International Journal of Recent Technology and Engineering*, *8*(3): 3639-3648.

[17]. Bahrami, A. and Yavari M. (2019). Hysteretic assessment of steel-concrete composite shear walls. *International Journal of Recent Technology and Engineering*, *8*(2): 5640-5645.

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