STRUCTURAL PERFORMANCE OF HIGH STRENGTH CONCRETE-FILLED SQUARE STEEL TUBE COLUMNS UNDER COMBINED COMPRESSION AND BENDING

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A numerical investigation into the structural performance of high strength concrete-filled square steel tube columns under combined compression and bending is presented in this paper. Finite element (FE) models were developed and validated to accurately replicate the experimental results presented in literature for the columns subject to combined compression and bending. Parametric studies using the validated FE models were performed to examine the performance of high strength concrete-filled square steel tube columns with varying high strength steel and concrete grades and relative slenderness values and subject to different combinations of compression and bending. The applicability of design methods in European and American standards to these columns under combined compression and bending was also evaluated based on the results of parametric studies in this paper and experiments reported in literature. It has been found through the evaluation that the design methods in European and American standards provide conservative strength predictions for high strength concrete-filled square steel tube columns subject to combined compression and bending. Therefore, these design methods can be safely applied to high strength concrete-filled square steel tube columns under combined compression and bending.

Keywords: High strength steel and concrete, concrete-filled steel tube columns, square section, combined compression and bending, finite element modeling, design.

1 Introduction

Concrete-filled steel tube (CFST) structures have been widely applied in buildings and bridges since the structures demonstrate high load-carrying capacity, disaster resistance and constructability (Uy, 2001; Lai and Varma 2015). High strength steel (HSS) with nominal yield strength above 460MPa and high strength or ultra-high strength concrete with nominal compressive strength above about 60MPa and up to 180MPa are also available in the market and can be used to form CFST structures with reduced structural sizes to lower the embodied carbon footprint of structures. However, existing design rules including European and American standards (EN1994-1-1 2004; AISC 360 2016) specify a narrow range of material strengths for structural design. Based on these standards, the design methods in the standards cover the CFST members made of steel with nominal yield strength up to 525MPa and concrete with nominal compressive strength up to 70MPa. Therefore, the behavior of the structures formed using high strength steel and concrete and subject to various critical loads needs to be clearly understood in order to accurately design those CFST structures. This study focuses on the high strength square CFST structures subject to combined compression and bending.

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Research studies have been conducted to investigate the behavior of high strength square CFST structures subject to combined compression and bending. Xiong and co-researchers tested three high strength square CFST columns under combined compression and bending (Xiong et al. 2017) and the columns were formed using HSS with yield strength (f_y) of 465 and 756MPa and high strength concrete with cylinder compressive strength ($f_{c'}$) of 176-183MPa. Four high strength square CFST columns made of HSS with f_y of 488MPa and concrete with cube compressive strength (f_{cu}) of 43.2 and 55.3MPa were also tested under combined compression and bending by Du and co-researchers (Du et al. 2017). In the study of Lee et al (Lee et al. 2017), one high strength square CFST columns made of HSS with f_y of 746MPa and concrete with $f_{c'}$ of 70.5MPa were tested under combined compression and bending. It was also found by Lee et al (Lee et al. 2017) that American standard provides quite conservative strength prediction for the structure. Liu (2004) experimentally investigated high strength square CFST columns under combined compression and bending and the columns were made of high strength steel with f_y of 550MPa and concrete with f_{cu} of 70.8 and 82.1MPa. Liu also found that European standard provides slightly unconservative strength predictions for the specimens. The review of the above studies shows that limited experiments have been conducted, covering discrete combinations of high strength steel and concrete for the members.

Therefore, behavior of high strength square CFST columns with a wide range of dimensions and material strengths and subject to combined compression and bending was investigated numerically in this study. Finite element (FE) models were developed and validated using the experimental results reported in the above studies. The validated FE models were applied for parametric studies. Effects of confinement factor and column relative slenderness values were examined. The accuracy of design methods in European and American standards was assessed using the experimental results in literature and parametric studies results and discussed in this study.

2 FE Modeling

2.1 *FE models*

FE modeling was performed using ABAQUS software package for high strength square CFST columns subject to combined compression and bending. Solid elements (C3D8R) were applied for both core concrete and the steel tube of each CFST column. A mesh size of cross-section width over ten was selected based on mesh sensitivity studies. The stress-strain relationship of HSS was obtained using multi-linear stress-strain curve models recommended by Ban and Shi (2018) and converted into true stress-logarithmic plastic strain curves which were incorporated into the FE models. As for the input of concrete material properties, the elastic stress-strain behavior of the material was simulated using the elastic modulus and the Poisson ratio of 0.2. Since the compressive strength and ductility of concrete can be enhanced due to the confinement effect provided by the outer steel tube for each CFST column, the stress-strain model proposed by Han et al. (2007) and taken into account the steel tube confinement effect has been adopted in this study and the obtained stress-strain relationship was incorporated into the concrete damaged plasticity model for FE models. Tensile properties of concrete were also required for the concrete damaged plasticity model. The tensile strength was taken as 10% of the cylinder compressive strength of concrete (Du et al. 2017) while the fracture energy values calculated based on the model given in (ABAQUS 6.14) were incorporated into the models.

In order to simulate the interface between the steel tube and concrete for each CFST column, a surface-to-surface contact was applied. Hard contact was defined at the normal direction while the Coulomb friction model in the tangential direction was applied with the friction factor value of 0.25 (Ellobody and Young 2006). The pin-ended boundary conditions were applied using two eccentric reference points. The longitudinal distance between the reference points represents the effective length of each structure. Each reference point was coupled with the nodes of the end surface of each column and restrained against all degrees of freedom except for the rotation around the buckling axis. At the reference point on the loaded side, the longitudinal displacement was allowed. Static loading was applied to the reference point on the loaded side by specifying a displacement rate.

2.2 *Validation*

The FE modeling results are compared with experimental results in literature (Du et al 2017; Lee et al 2017; Liu, 2004; Xiong et al 2017) in order to validate the FE models. The ultimate loads ($N_{u,FE}$) predicted by the FE modeling are provided in Table 1 in comparison with those ($N_{u,exp}$) obtained from experiments. In Table 1, the f_c' for specimens tested by Du et al (2017) and Liu (2004) were estimated based on the f_{cu} values given in the experimental investigations. As can be seen in Table 1, the ultimate loads of the specimens were accurately predicted using the FE models. The mean value of $N_{u,FE}/N_{u,exp}$ ratios was estimated to be 1.00 with coefficient of variation (COV) of 0.02. Typical load-mid deflection curves from FE modeling are presented in Figure 1 together with experimental results. Failure modes of specimens can also be well predicted, as shown in Figure 2. Therefore, the FE models can accurately replicate the experimental results of high strength square CFST columns subject to combined compression and bending.

Table 1. Comparison of $N_{u,FE}$ with $N_{u,exp}$.

Reference	Specimen	f_y (MPa)	f_c' (MPa)	$N_{u,exp}$ (kN)	$N_{u,FE}$ (kN)	$N_{u,FE}/N_{u,exp}$
Xiong et al (2017)	SS-1	465.0	183.0	5187	5030	0.97
	SS-2	756.0	176.0	7136	6949	0.98
Du et al (2017)	SC40-150-0.2	488.4	34.6	2470	2442	0.99
	SC50-150-0.2	488.4	45.3	2450	2485	1.01
	SC40-150-0.4	488.4	34.6	2042	1982	0.97
	SC50-150-0.4	488.4	45.3	2020	2033	1.01
Lee et al (2017)	E1	746	70.5	6491	6742	1.04
Liu (2004)	E03	550	60.8	1330	1316	0.99
	E04	550	72.1	1020	1016	1.00
					Mean	1.00
					COV	0.02

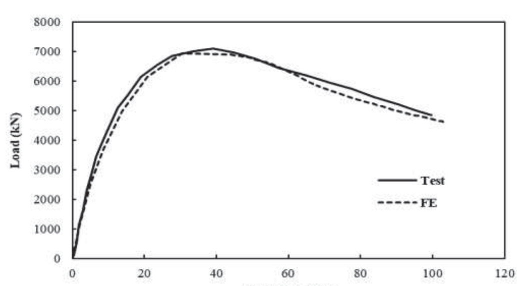

Figure 1. Load-mid deflection curve for SS-2 from FE modeling and the experiment (Xiong et al 2017).

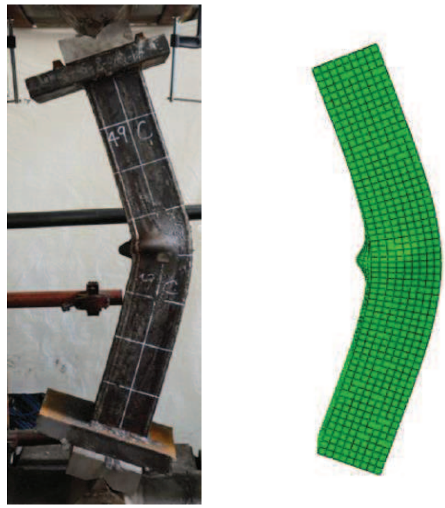

Figure 2. Failure mode of SC50-150-0.2 from FE modeling and the experiment (Du et al 2017).

3 Parametric Studies

3.1 *General*

The validated FE models were applied to perform systematic parametric studies on high strength square CFST columns with a wide range of dimensions, steel grades and concrete compressive strengths and subject to different combinations of compression and bending. Effects of confinement factor and relative slenderness value were also investigated. The cross-sectional dimensions of CFST columns for parametric studies were selected based on those used for experiments listed in Table 1. No influence of local buckling in the steel tubes of CFST columns for parametric studies is expected since the cross-sectional dimensions satisfy the requirements specified in European standard (EN1994-1-1 2004). Steel grades of S460, S690 and S960 were considered while cylinder compressive strength of 90, 120 and 180MPa for high strength and ultra-high strength concrete were used. The length of columns was varies in order to obtain different member slenderness values between 0.6 and 1.8. Different combinations of compression and bending were achieved by varying the initial loading eccentricity (e). The values for e were chosen in relation to the cross-sectional width (h) and the initial loading eccentricity ratio (ε_r) as the ratio of e over h. The ε_r values from 0 to 4.0 were selected for parametric studies. Initial global geometric imperfections with the magnitude given in European standard (EN1994-1-1 2004) of column length over 300 were incorporated in the modeling for parametric studies in the form of the lowest buckling mode shape obtained through conducting separate eigenvalue analysis. This global imperfection magnitude is larger than that given in American standard (AISC 360 2016), aiming to evaluate the applicability of the standards on the safe side.

Confinement factor (ξ) defined as A_sf_y/A_cf_c' has been suggested to significantly affect the structural performance of concrete-filled steel tube structures (Han et al 2007; Lai et al 2016). The A_s and A_c are the cross-sectional areas of steel tube and concrete in-fill respectively. Its effect on the high strength square CFST columns subject to combined compression and bending was investigated in this study using the cross-sections with width of 200mm and steel plate thicknesses of 12.5 and 12mm. These cross-sections were chosen since the bending capacity of the members was measured by Xiong et al (2017) and used in this study for deriving the interaction curves of compression load versus bending moment. For the member with steel plate thickness of 12.5mm, the ξ equals to 0.791 with f_y of 465 MPa and f_c' of 180MPa. As for the member with steel plate thickness of 12mm, the ξ equals to 1.223 with f_y of 756 MPa and f_c' of 180MPa. The member slenderness value of 0.6 was applied for these members. The interaction curves of compression load versus bending moment obtained for the members were compared, as discussed in Section 3.2.

Effect of relative slenderness (λ) values on the high strength square CFST columns subject to combined compression and bending was also investigated using the cross-section with the width of 200mm, steel plate thicknesses of 12.5mm, f_y of 465 MPa and f_c' of 180MPa. Various lengths leading to λ values of 0.6, 1.2 and 1.8 estimated based on European standard (EN1994-1-1 2004) were used. The interaction curves of compression load versus bending moment obtained for the members with different member slenderness values were compared, as discussed in Section 3.3.

3.2 *Effect of confinement factor*

The $N_{u,FE}$ and the corresponding maximum moment ($M_{u,FE}$) for CFST columns with different confinement factor (ξ) values were investigated based on varying ε_r values from 0 to 3.0 for different combinations of compression and bending. The resultant $N_{u,FE}$ and $M_{u,FE}$ were normalized by the ultimate load ($N_{u,\varepsilon r=0}$) for the column under pure compression and the bending moment capacity ($M_{u,exp}$) of the structures measured under pure bending by Xiong et al (2017). The normalized $N_{u,FE}$ versus $M_{u,FE}$ curves are plotted in Figure 3. As can be seen in the figure, the normalized $N_{u,FE}$ versus $M_{u,FE}$ curves are significantly affected by the ξ values. The ratios of $N/N_{u,FE}$ and $M/M_{u,FE}$ that define the balance point locations decrease with increasing ξ values. As the ξ value increases, the strength proportion of a CFST column contributed from the steel tube increases, leading to lower strength proportion contributed from the in-filled concrete to bending moment capacity at the balance point.

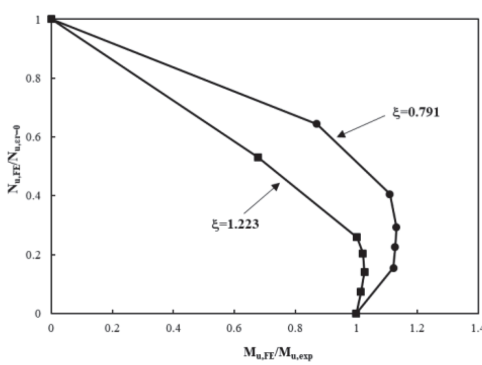

Figure 3. Effect of confinement factor on the normalized N-M interaction curve of high strength square CFST columns.

3.3 *Effect of relative slenderness value*

The $N_{u,FE}$ and the corresponding maximum moment ($M_{u,FE}$) for CFST columns with different λ values were also investigated based on varying ε_r values from 0 to 3.0 for different combinations of compression and bending. The resultant $N_{u,FE}$ and $M_{u,FE}$ were normalized by the ultimate load ($N_{u,\varepsilon r=0}$) for the column under pure compression and the bending moment capacity ($M_{u,exp}$) of the structures measured under pure bending by Xiong et al (2017). The normalized $N_{u,FE}$ versus

$M_{u,FE}$ curves are plotted in Figure 4. It can be seen in the figure that the shapes of normalized $N_{u,FE}$ versus $M_{u,FE}$ curves are insensitive to λ values.

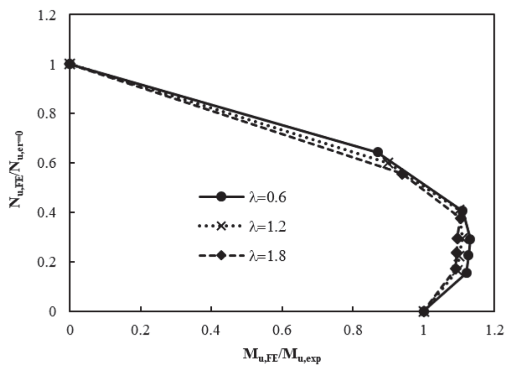

Figure 4. Effect of member relative slenderness value on the normalized N-M interaction curve of high strength square CFST columns.

4 Design Methods

4.1 *European standard*

The applicability of the specifications provided in European standard (EN1994-1-1 2004) to high strength square CFST columns under combined compression and bending was assessed using the results of parametric studies introduced in Section 3.1 and the experimental results reported in literature (Du et al 2017; Lee et al 2017; Liu, 2004; Xiong et al 2017). The unfactored ultimate loads ($N_{u,EC4}$) for the CFST columns subject to combined compression and bending were predicted using the load-bending moment interaction relationship and design methods given for the structures subject to pure compression or bending. The comparison between the $N_{u,EC4}$ and $N_{u,exp+FE}$ obtained from experiments reported in literature and parametric studies in Section 3.1 is presented in Figure 5. It can be seen in the figure that the $N_{u,EC4}$ values predicted based on European standard agree reasonably well with the $N_{u,exp+FE}$ values. The mean value of $N_{u,exp+FE}/N_{u,EC4}$ equals to 1.20 with COV of 0.10, as shown in Table 2. Therefore, the design method based on European standard provide conservative strength predictions for the structures.

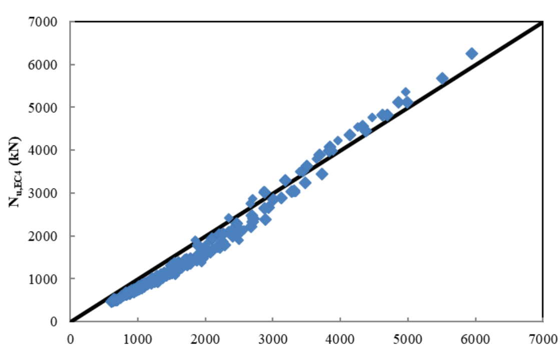

Figure 5. Comparison of $N_{u,exp+FE}$ with the strength predictions ($N_{u,EC4}$) based on European standard.

Table 2. Comparison between strength predictions based on standards with parametric studies results in this study and experimental results in literature.

	European standard $N_{u,exp+FE}/N_{u,EC4}$	American standard $N_{u,exp+FE}/N_{u,AISC}$
Mean	1.20	1.25
COV	0.10	0.14

4.2 *American standard*

The applicability of the specifications provided in American standard (AISC 360 2016) to high strength square CFST columns under combined compression and bending was also evaluated using the results of parametric studies introduced in Section 3.1 and the experimental results reported in literature (Du et al 2017; Lee et al 2017; Liu, 2004; Xiong et al 2017). The unfactored ultimate loads ($N_{u,AISC}$) for the CFST columns subject to combined compression and bending were predicted using the load-bending moment interaction relationship and design methods given for the structures subject to pure compression or bending. The calculated $N_{u,AISC}$ values are compared with the $N_{u,exp+FE}$ values obtained from experiments reported in literature and parametric studies in Section 3.1 in Figure 6. As can be seen in the figure, the American standard primarily provide conservative strength predictions since most of $N_{u,AISC}$ values are lower than the $N_{u,exp+FE}$ values. The mean value of $N_{u,exp+FE}/N_{u,AISC}$ ratios is 1.25 with COV of 0.14, as given in Table 2. Comparing with the strength predictions ($N_{u,EC4}$) based on European standard (EN1994-1-1 2004), the strength predictions ($N_{u,AISC}$) based on American standard (AISC 360 2016) are more conservative on an average basis.

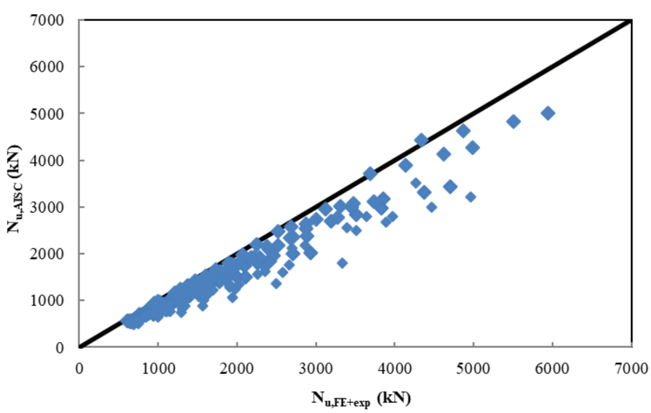

Figure 6. Comparison of $N_{u,exp+FE}$ with the strength predictions ($N_{u,AISC}$) based on American standard.

5 Conclusions

Structural performance of high strength concrete-filled square steel tube columns under combined compression and bending was investigated numerically in this study. FE models were developed and validated against experimental results reported in literature. Parametric studies were subsequently carries out on these structures with a wide range of dimensions and different steel and concrete material strength. The effect of confinement factor was examined and found to be significant for the high strength concrete-filled square steel tube columns under combined compression and bending. The effect of relative slenderness ratio was also investigated and found to be quite limited for the structures. The applicability of design rules in European and

American standards to the high strength concrete-filled square steel tube columns under combined compression and bending was also evaluated using the parametric studies results and the experimental results reported in literature. The evaluation shows that both standards provide conservative strength predictions for the structures. The strength predictions obtained based on American standard are more conservative than those obtained based on European standards.

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