WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.146099
ARCHIVES OF CIVIL ENGINEERING
Vol. LXIX ISSUE 3 2023

pp. 587 –596

Research paper

Mechanical properties of CFST short columns with different void ratios

Junxi Song[1], Zhuowei Han[2], Dawei Wang[3], Xiaorui Lu[4]

Abstract: In order to study the mechanical behavior of concrete-filled steel tube(CFST) short column with different void ratios under a certain eccentricity. A fiber model of concrete-filled steel tube section with different void heights was established. Compared with existing model test data, the axial force and flexural moment strength models of concrete-filled steel tube columns with different void ratios were established. The results show that, in the case of different void ratios, the cross-section strength envelope shows an overall contraction tendency with the increase of void ratio, and each line is basically parallel. A model for calculating the coefficient of axial load degradation was established. The Han's flexural moment strength model of the flexural component was revised, and the strength model of concrete-filled steel tube column under eccentric compression considering void ratio was established, which provides a theoretical basis and method for the safety assessment during the operation of concrete-filled steel tube arch bridges.

Keywords: concrete-filled steel tubes, eccentric compression, finite element analysis, mechanical behavior, void ratio

---

[1] M.E., Second Engineering Co.Ltd of CCCC Fourth Highway Engineering Co.Ltd, Beijing 100176, China, e-mail: 2998184482@qq.com, ORCID: 0009-0008-1168-8943

[2] M.E., Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China, e-mail: 249192408@qq.com, ORCID: 0000-0002-6072-2887

[3] M.E., Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China, e-mail: 823499748@qq.com, ORCID: 0000-0003-0803-9391

[4] M.E., Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China, e-mail: 2543445581@qq.com, ORCID: 0009-0001-3806-4603

1. Introduction

CFST structure is widely used in housing construction and bridge engineering [1–3]. However, the problem of core concrete and steel tube voiding (including debonding) has always been the research focus of scholars. Voiding (including debonding) is a very dangerous bridge disease, which has a fatal impact on the service performance and life of CFST structures, increasing the deformation of bridge structure during operation and reducing its bearing capacity. Therefore, it is practical to research the voiding problem of concrete-filled steel tubes [4–7].

The mechanical behavior of concrete filled steel tubular columns without voids has been studied extensively, mainly in flexural moment and torsional shear. Yan et al. [8] conducted experimental and analytical research on the structural performance of eccentrically compressed circular reinforced concrete columns, proposed a modified plastic stress distribution method to predict the critical section resistance of columns, and established a formula to estimate the effective stiffness of columns. Nie et al. [9] proposed a simplified design equation for calculating the bending-shear-torsion bearing capacity of CFST short columns through experimental research and analysis of the ultimate bearing capacity of CFST short columns under bending-shear-torsion coupling loads. Ding et al. [10] presented experimental and numerical studies on the behavior of both circular and square CFST short columns under local compression, proposed an analytical formula for calculating the local compression bearing capacity of CFST short columns. Tokarz [1] conducted a test study on the stability of the arc arch, La Poutre and Snijder [11] conducted an inelastic out-of-plane stability test on a circular steel arch subjected to concentratiod loads on the vault, and found that the important factor affecting the out-of-plane stability of the arch rib was the torsional stiffness of the vault.

However, there are relatively few studies on the mechanical properties of CFST columns after Disengaging. Liao et al. [12, 17, 18] tested the mechanical properties of 21 CFST specimens with different initial imperfections, and studied the influence of gap on the failure mode, ultimate strength and bending stiffness of CFST columns or beams. Xue et al. [13] studied the debonding effect of concrete-filled steel tubular short columns through experiments, established the finite element model of concrete-filled steel tubular circular short columns through ABAQUS, and proposed a simplified formula for calculating the debonding effect. Liu [14] studied the debonding caused by the temperature change and shrinkage of CFST through experiments, and concluded that the concrete strength has little influence on the bond strength, while the surface condition of steel has a great influence on it, and indicated that debonding will lead to the reduction of the bearing capacity of concrete-filled steel tube arch. Wang et al. [15, 16] conducted an experimental study on the axial compression performance of CFST short columns with circumferential gaps. The research results indicate that, due to the weakening of steel tube restraint and concrete support, the existence of circumferential gap defects may lead to brittle cracking of concrete, inward and outward bulge of steel tubes. The axial compressive strength, initial stiffness and ductility of columns are also significantly reduced.

The research of the above literature has a guiding role in understanding the mechanical properties of the CFST column after disengaging, but there is no relevant report on the strength model of CFST column under axial force and flexural coupling effect after the void. This paper refers to the existing model test data of eccentric compressive bearing capacity of CFST short columns with voids. Based on the OpenSees platform, the modeling calculation of CFST short columns with different void ratios under a certain eccentricity is carried out. The influence of the void ratio on its mechanical properties is studied and analyzed, and the calculation results are compared with the existing experimental research results, which are in good agreement. Under different void ratios, the degradation coefficient of axial compressive bearing capacity and the axial moment strength model of CFST after disengaging are obtained. It provides a theoretical basis and method for the subsequent safety stress assessment of CFST arch bridges during operation.

2. Introduction to computational models

Han [12, 18, 19] used the knowledge of mathematical statistics to study and analyze a large amount of data from the CFST axial compression test, and studied the influence of the hoop coefficient ξ on the test results to obtain the one-dimensional stress-strain relationship model of the core concrete. The parameters of the model are rigorously set, and the corresponding coefficients are obtained by fitting and analyzing a large number of experimental data. It is a constitutive model suitable for finite element calculation research [20].

$$\sigma_c = \begin{cases} \sigma_0\left[A\dfrac{\varepsilon}{\varepsilon_0} - B\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^2\right] & \varepsilon \le \varepsilon_0 \\ \sigma_0(1-q) + \sigma_0 q\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^{0.1\xi'} & \varepsilon > \varepsilon_0, \quad \xi \ge 1.12 \\ \sigma_0\left(\dfrac{\varepsilon}{\varepsilon_0}\right)\dfrac{1}{\beta\left(\dfrac{\varepsilon}{\varepsilon_0}-1\right)^2+\left(\dfrac{\varepsilon}{\varepsilon_0}\right)} & \varepsilon > \varepsilon_0, \quad \xi < 1.12 \end{cases} \tag{2.1}$$

where: $\sigma_0 = f_{ck}\left[1.194 + (13/f_{ck})^{0.45}\left(-0.07185\xi'^2 + 0.5789\xi'\right)\right]$, e_0 is the axial strain of the section centroid and can be expressed as $\varepsilon_0 = \varepsilon_c + 1400 + 800\left(\dfrac{f_{ck}-20}{20}\right)\xi^{0.2}$, ε_c is the strain at the peak point of the stress-strain curve of ordinary concrete and can be expressed as $\varepsilon_c = 1300 + 14.93 f_{ck}$, $A = 2 - k$, $B = 1 - k$, $k = 0.1\xi'^{0.745}$, $\beta = 5e^{-4}(2.36 \times 10^{-5})^{[0.25+(\xi-0.5)^7]} f_{ck}^2$, $q = k/(0.2 + 0.1\xi')$, A_s is steel tube area, A_c is core concrete area, f s is ultimate yield strength of steel, f_{ck} is concrete axial compressive strength, ξ' is the modified hoop coefficient and can be expressed as $\xi' = k_e\xi$, the correction coefficient k_e is a function of the eccentricity e/r_c as a variable. If $e/r_c \le 1.0$, $k_e = 1 - e/r$ and if $e/r_c > 1.0$, $k_e = 0$. e is eccentricity, r_c is radius of concrete filled steel tube. ξ is the standard value of the constraint effect coefficient and can be calculated by $\xi = \dfrac{A_s f_s}{A_c f_{ck}}$.

The void phenomenon of CFST will change the stress area and three-dimensional stress state of concrete and also weaken the hoop effect of steel tube on concrete. The hoop coefficient is corrected by the reduction factor k_d of the void ratio. The mathematical expression between the void ratio reduction coefficient k_d and void ratio ρ is as Eq. 2.2,

$$k_d = 0.7991 - 9.03\rho \tag{2.2}$$

where k_d – void ratio reduction coefficient, ρ – void ratio.

Based on the core concrete constitutive relationship model proposed by Han, the influence of the eccentricity correction coefficient k_e and the void ratio reduction coefficient k_d on the hoop effect of the CFST is further considered, and a new hoop coefficient is obtained as the Eq. 2.3,

$$\xi_d' = k_e k_d \xi \tag{2.3}$$

Substitute ξ_d for ξ and bring in Eq. 2.1 to obtain the stress-strain curve of the core concrete after considering the eccentricity and void ratio.

Based on the OpenSees software, the section moment and curvature analysis is carried out. The OpenSees software provides a fiber model as shown in Fig. 1. The displacement function of the three-dimensional fiber beam element adopts the displacement function of the Euler-Bernoulli beam. The axial strain at any point on the section is,

$$\varepsilon_{11} = \varepsilon_0 - yv + zw \tag{2.4}$$

where ε_{11} – the axial strain at any point on the section, y – the y-axis coordinate of the fiber on the local coordinate y-z, z – the z-coordinate of the fiber on the local coordinate y-z, v – the second-order offset derivative of local coordinate system displacement in y-coordinate, w – the second-order offset derivative of local coordinate system displacement in z-coordinate.

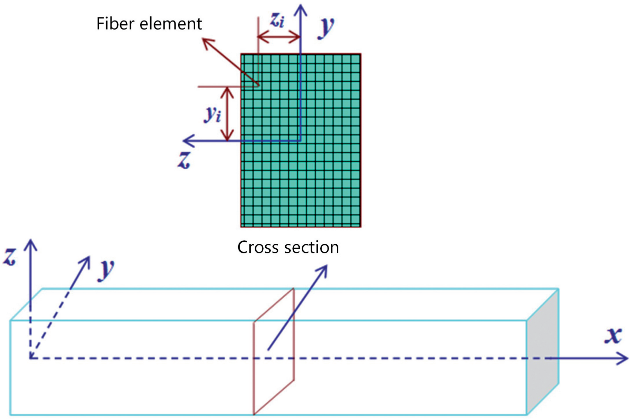

Fig. 1. Three-dimensional fiber beam unit

Limited to the length of the article, this paper will not introduce the fiber unit in detail, and the theory of specific fiber unit can be produced in the literature [21, 22].

3. Analysis of calculation results

Liu [23] conducted eccentric compression tests on CFST short columns with void ratio of 0–1.24%, outer diameter of 168 mm, wall thickness of 5 mm, length of 500 mm, and filled with C50 concrete. The outer diameter of the steel tube is 168 mm and the thickness is 5 mm. The length of the short column specimen is 500 mm, and the length of the long column specimen is 1000 mm. The yield strength of the steel is 330 MPa. The measured cubic compressive strength of concrete is 56 MPa. The model test results are shown in Table 1 [23].

Table 1. The result of Model test

No.	Specimen	Void height h [mm]	Void ratio [%]
1	Seh1-20-0	0	0
2	Seh2-20-0		
3	Seh1-20-4	4	0.68
4	Seh2-20-4		
5	Seh1-20-8	8	1.90
6	Seh2-20-8		
7	Seh1-20-12	12	3.47
8	Seh2-20-12		
9	Seh1-20-18	18	6.30
10	Seh2-20-18		
11	Seh1-20-26	26	10.76
12	Seh2-20-26		

Note: 1) In the specimen number, 20 is the initial eccentric distance e_0 (mm) 0, 4, 8, 12, 18, 26 are the void height h (mm);
2) void ratio = (core concrete area – void volume empty area) / core concrete area.

In this paper, based on the OpenSees platform, a finite element model of CFST short column is established. The model dimensions and material parameters were consistent with Liu's [23] test. The stress-strain relationship curve can be obtained as shown in Fig. 2.

The cross-section fiber partition of the experimental model is illustration in Fig. 3. Considering the steel tube, core concrete and the internal void height of CFST, the section fiber model is calculated and analyzed under the coupling effect of axial force and flexural moment. The specific loading diagram is shown in Fig. 4.

The calculation results of different void ratios are further analyzed, and a total of 72 models are calculated, respectively considering different void ratios and different initial axial pressures. The cross-sectional strength envelopes of the 72 calculation models are summarized in Fig. 5.

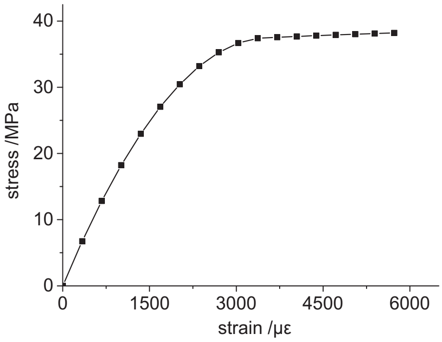

Fig. 2. The stress- strain curve of core concrete

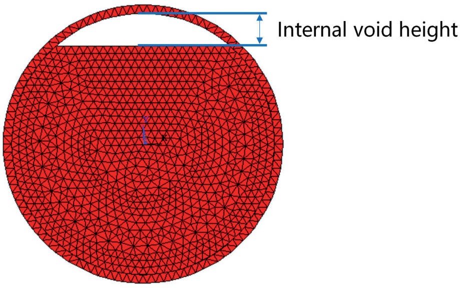

Fig. 3. Section fiber partitioning

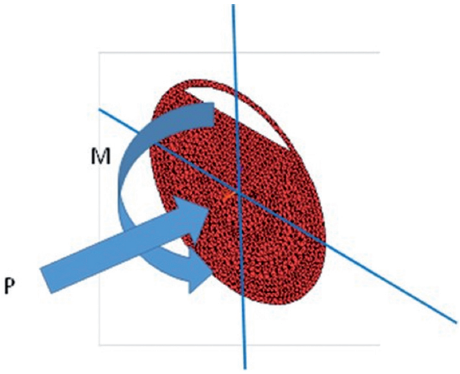

Fig. 4. The composite of axial force and flexural moment

From the analysis of Fig. 5. it can be seen that in the case of different void ratios, the cross-section strength envelope shows an overall contraction tendency with the increase of void ratio, the lines are basically parallel. Therefore, the strength degradation law of eccentrically compressed voided CFST members can be analyzed according to the degradation law of axial compression bearing capacity.

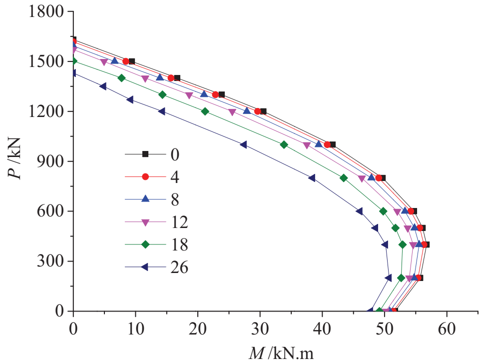

Fig. 5. Section strength envelope under the combined action of compression and flexural at different Void height

Further comparison of the experimental and numerical simulation results (Table 2), Fig. 6. can be obtained.

Table 2. Comparison of the test results with numerical simulation results

Height [mm]	Void ratio [%]	TEST [kN]	FEM [kN]
0	0	1610	1277
4	0.0068	1410	1266
8	0.019	1300	1246
12	0.0347	1260	1218
18	0.063	1200	1171
26	0.1076	1130	1096

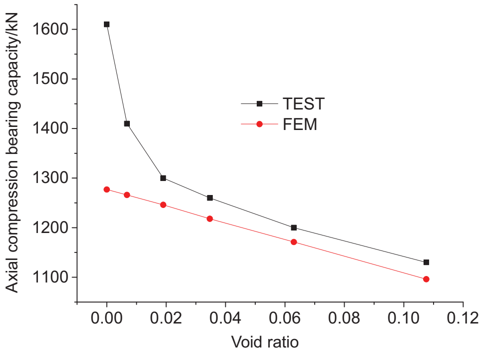

Fig. 6. Comparison of the test results with numerical simulation results

It can be seen from Fig. 6. that there are some differences in the attenuation law of axial compression bearing capacity between the test and numerical analysis under the condition of small void ratio. However, due to the number of CFST columns tested is not very large, and there are certain errors in the discreteness of concrete strength and the test itself. Therefore, the law of linear descent is finally selected, and the degradation coefficient of axial compression bearing capacity is established, D is the slope of the linear segment of FEM and test data in Fig. 6, it represents the relationship between the axial compressive bearing capacity and void ratio of CFST.

$$D = 1 - 1.32\rho \tag{3.1}$$

where: D – degradation coefficient, ρ – void ratio.

4. Model of axial force and moment strength of concrete filled steel tube after disengaging

Referring to the section flexural moment strength model of buckling members proposed by Han, ξ_o and η_o can be approximately expressed as a function of the restraint effect coefficient ξ, and ξ_o, η_o can be calculated by,

$$\xi_o = 1 + 0.18\xi^{-1.15} \tag{4.1}$$

$$\eta_o = \begin{cases} 0.5 - 0.245 \cdot \xi & (\xi \leq 0.4) \\ {[2pt]}0.1 + 0.14 \cdot \xi^{-0.84} & (\xi > 0.4) \end{cases} \tag{4.2}$$

Further considering the influence factor of the slenderness ratio of the member, the N/N_u – M/M_u correlation equation of the CFST compressive member is obtained as follows,

$$\begin{cases} \dfrac{1}{\varphi} \cdot \dfrac{N}{N_{uo}} + \dfrac{a}{d} \cdot \left(\dfrac{M}{M_u}\right) = 1 & (N/N_{uo} \geq 2\varphi^3 \cdot \eta_o) \\ -b \cdot \left(\dfrac{N}{N_{uo}}\right)^2 - c \cdot \left(\dfrac{N}{N_{uo}}\right) + \dfrac{1}{d} \cdot \left(\dfrac{M}{M_u}\right) = 1 & (N/N_{uo} < 2\varphi^3 \cdot \eta_o) \end{cases} \tag{4.3}$$

where $a = 1 - 2\varphi^2 \cdot \eta_o$; $b = \dfrac{1 - \xi_o}{\varphi^3 \cdot \eta_o^2}$; $c = \dfrac{2 \cdot (\xi_o - 1)}{\eta_o}$; $d = 1 - 0.4 \cdot \left(\dfrac{N}{N_E}\right)$, $1/d$ is the magnification factor of the flexural moment that considering the second-order effect, N_E is the Euler's critical force, φ is the axial compression stability coefficient, N_{uo} is the axial strength bearing capacity, M_u is the flexural capacity.

Further modifying the Han's model, the strength model considering the void ratio is as follows,

$$\begin{cases} \dfrac{1}{\varphi} \cdot \dfrac{N}{N_{uo}} + \dfrac{a}{d} \cdot \left(\dfrac{M}{M_u}\right) = 1 - 1.32\rho & (N/N_{uo} \geq 2\varphi^3 \cdot \eta_o) \\ -b \cdot \left(\dfrac{N}{N_{uo}}\right)^2 - c \cdot \left(\dfrac{N}{N_{uo}}\right) + \dfrac{1}{d} \cdot \left(\dfrac{M}{M_u}\right) = 1 - 1.32\rho & (N/N_{uo} < 2\varphi^3 \cdot \eta_o) \end{cases} \tag{4.4}$$

Based on the established strength model of CFST column under eccentric compression, a theoretical basis and method for the subsequent safety stress assessment of CFST arch bridges during operation is provided.

5. Conclusions

In this paper, based on the OpenSees platform, a CFST section fiber model is established, and the numerical model is verified by the test results. Through the comparison of the numerical analysis and the experimental results under the coupling action of axial force and flexural moment, the following conclusions are drawn:

1. In the case of different void ratios, the cross-section strength envelope shows an overall contraction tendency with the increase of void ratio, and the lines are basically parallel.
2. The strength degradation law of voided CFST members under eccentric compression can be analyzed according to the degradation law of axial compressive bearing capacity. Through the comparative analysis of experimental and numerical solutions, it is established that the axial compressive bearing capacity degradation coefficient is: $D = 1 - 1.32\rho$.
3. The section flexural moment strength model of the Han's was revised, and the strength model of CFST column under eccentric compression considering the void ratio was obtained, which provided a theoretical basis and method for the subsequent safety assessment of CFST arch bridges during operation.

References

[1] F.J. Tokarz, "Experimental study of lateral buckling of arches", *Journal of the Structural Division*, vol. 97, no. 2, pp. 545–559, 1971, doi: 10.1061/JSDEAG.0002816.

[2] K.A. Farhan and M.A. Shallal, "Experimental behaviour of concrete-filled steel tube composite beams", *Archives of Civil Engineering*, vol. 64, no. 2,pp. 235–251, 2020, doi: 10.24425/ace.2020.131807.

[3] Z.R. Lu and C. Guo, "A study on RCFST column instability modes", *Archives of Civil Engineering*, vol. 68, no. 2, pp. 211–225, 2022, doi: 10.24425/ace.2022.140638.

[4] M.N. Baig, J.S. Fan, and J.G. Nie, "Strength of concrete filled steel tubular columns", *Tsinghua Science & Technology*, vol. 11, no. 6, pp. 657–666, 2006, doi: 10.1016/S1007-0214(06)70248-6.

[5] C.W. Roeder, B. Cameron, and C.B. Brown, "Composite action in concrete filled tubes", *Journal of Structural Engineering*, vol. 125, no. 5, pp. 477–484, 1999, doi: 10.1061/(ASCE)0733-9445(1999)125:5(477).

[6] G.C. Li, B.W. Chen, Z.J. Yang, and Y.H. Feng, "Experimental and numerical behaviour of eccentrically loaded high strength concrete filled high strength square steel tube stub columns", *Thin-Walled Structures*, vol. 127, no. 6, pp. 483–499, 2018, doi: 10.1016/j.tws.2018.02.024.

[7] S.L. Chen, C. Hou, H. Zhang, and L.H. Han, "Structural behaviour and reliability of CFST trusses with random initial imperfections", *Thin-Walled Structures*, vol. 143, no. 10, 2019, doi: 10.1016/j.tws.2019.106192.

[8] B. Yan, X.H. Zhou, and J.P. Liu, "Behavior of circular tubed steel-reinforced-concrete slender columns under eccentric compression", *Journal of Constructional Steel Research*, vol. 155, no. 4, pp. 342–354, 2019, doi: 10.1016/j.jcsr.2018.11.018.

[9] X. Nie, Y.H. Wang, S. Li, and J. Chen, "Coupled bending-shear-torsion bearing capacity of concrete filled steel tube short columns", *Thin-Walled Structures*, vol. 123, no. 2, pp. 305–316, 2018, doi: 10.1016/j.tws.2017.11.026.

[10] F.X. Ding, J. Liu, X.M. Liu, Z.W. Yu, and D.W. Li, "Mechanical behavior of circular and square concrete filled steel tube stub columns under local compression", *Thin-Walled Structures*, vol. 94, no. 11, pp. 155–166, 2015, doi: 10.1016/j.tws.2015.04.020.

[11] D.B. la Poutre, H.H. Snijder, and J.C.D. Hoenderkamp, "Spatial stability experiment on a semicircular steel arch", in *Proceedings of Advances in Structures-Steel, Concrete, Composite and Aluminium.* Sydney: A.A. Balkema Publisher, 2003, pp. 207-212.

[12] F.Y. Liao, L.H. Han, and S.H. He, "Behavior of CFST short column and beam with initial concrete imperfection: experiments", *Journal of Constructional Steel Research*, vol. 67, no. 12, pp. 1922–1935, 2011, doi: 10.1016/ j.jcsr.2011.06.009.

[13] J.Q. Xue, B. Briseghella, and B.C. Chen, "Effects of debonding on circular CFST stub columns", *Journal of Constructional Steel Research*, vol. 69, no. 1, pp. 64–76, 2012, doi: 10.1016/j.jcsr.2011.08.002.

[14] Z.Y. Liu, "Experiment study on interfacial normal bond strength of concrete filled steel tube", *Advanced Materials Research*, vol. 594–597, pp. 947–954, 2012, doi: 10.4028/www.scientific.net/AMR.594-597.947.

[15] Q.H. Shen, J.F. Wang, and J.Z. Li, "Experimental, numerical and design investigations on the performance of axially-loaded ECFT stub columns with spherical-cap gaps", *Structures*, vol. 46, no. 12, pp. 109–127, 2022, doi: 10.1016/j.istruc.2022.10.022.

[16] J.F. Wang, W. Liu, Q.H. Shen, J.Z. Li, and Z.H. Han, "Experimental investigation and theoretical analysis of axially-loaded concrete-filled elliptical tubes with circumferential gaps", *Thin-Walled Structures*, vol. 181, no. 12, 2022, doi: 10.1016/j.tws.2022.110100.

[17] F.Y. Liao and Y.J. Li, "Experimental behaviour of concrete filled steel tubes (CFST) with initial concrete imperfection subjected to eccentric compression", in *Trans Tech Publications. Advanced Building Materials and Sustainable Architecture: Selected, peer reviewed papers from the 2nd International Conference on Civil Engineering, Architecture and Building Materials (CEABM 2012), May 25–27, 2012, Yantai, China*. 2012, pp. 33–36.

[18] F.Y. Liao, L.H. Han, and Z. Tao, "Behaviour of CFST stub columns with initial concrete imperfection: Analysis and calculations", *Thin-Walled Structures*, vol. 70, no. 9, pp. 57–69, 2013, doi: 10.1016/j.tws.2013.04.012.

[19] L.H. Han, Y. Ye, and F.Y. Liao, "Effects of core concrete initial imperfection on performance of eccentrically loaded CFST columns", *Journal of Structural Engineering*, vol. 142, no. 12, pp. 57–69, 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001604.

[20] B.C. Chen, Y.J. Chen, L.Y. Wang, and L.H. Han, "Study of stress-strain relation of concrete filled steel tubular eccentric compression column", *China Journal of Highway and Transport*, vol. 17, no. 1, pp. 28–32, 2004, doi: 10.19721/j.cnki.1001-7372.2004.01.007.

[21] C.A. Zeris and S.A. Mahin, "Analysis of reinforced concrete beam-columns under uniaxial excitation", *Journal of Structural Engineering*, vol. 114, no. 4, pp. 804–820, 1988, doi: 10.1061/(ASCE)0733-9445(1988)114:4(804).

[22] E. Spacone, F.C. Filippou, and F.F. Taucer, "Fibre beam-column model for non-linear analysis of R/C frames: Part 1. Formulation", *Earthquake Engineering & Structural Dynamics*, vol. 25, no. 7, pp. 711–725, 1996, doi: 10.1002/(SICI)1096-9845(199607)25:7<711::AID-EQE576>3.0.CO;2-9.

[23] X.P. Liu, C.H. Tang, S. Yang, K.H. Cai, and A.R. Liu, "Research on the influence of void ratio on the mechanical properties of eccentrically compressed concrete filled steel tubes", *Journal of Sun Yat sen University (Natural Science Edition)*, vol. 9, no. 3, pp. 40–44, 2010, doi: 10.3969/j.issn.1671-4229.2010.03.010.

Received: 2022-12-16, Revised: 2023-06-07