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Numerical Study on the axial compression performance of concrete-filled steel tubular hybrid columns

Zheng Lianqiong[1,2], Yang Hang1

[1] College of civil engineering, Fujian University of Technology, Fuzhou 350118, China;

[2] Fujian Provincial Key Laboratory of Advanced Technology and Informatization in Civil Engineering, Fuzhou 350118, China

Abstract: The mechanical properties of concrete filled steel tubular (CFST) hybrid columns subjected to axial compression were simulated by finite element method and compared with the experimental results. The calculated results are in good agreement with the experimental results. The variation of the cross-section strain along the cross section height is given before the peak load is reached, which is in accordance with the assumption of the flat section. On the basis of this, the thickness of the steel tube and the thickness of the reinforce concrete (RC) connecting plate are analysed. The research results show that the peak load is mainly determined by the bearing capacity of the RC connecting plate, and the concrete filled steel tubular column has better ductility after reaching the peak load.

1. Introduction

When the load eccentricity or the column slenderness is large, single concrete-filled steel tubular (CFST) members may unable to meet the structural function requirements, therefore, CFST built-up members formed by two or more CFST chords with hollow steel tubes have great potential to applied in heavy duty and large span structures, which will transform bending moment into axial force, and can give full play to the excellent compression performance of CFST members, increasing the radius of rotation of the section. However, the influence of shear deformation on the stability bearing capacity of the structure cannot be ignored in the built-up members, therefore, reinforced concrete (RC) plate were used to connect components at some of the roots of high CFST built-up piers [1] or the feet of CFST arch bridges [2] for improving of performance and economic benefit.

Seven CFST hybrid stub columns, which are composed of CFST members and connected by RC plate were tested under axial compression by Chen et al. [3] the main experimental parameters were the thickness of chord steel tube and thickness of RC plate. Then the load-bearing capacity of axially-loaded CFST hybrid stub column was proposed considering that the CFST member does not reach its ultimate resistance. Yan Qiaoling et al. [4] derived the portion of total load carried by the CFST longitudinal members corresponding to the crushing of RC plate based on the deformation compatibility equation, and the reduction coefficient of load-bearing capacity of CFST longitudinal members for different theory were presented based on numerical results. However, in previous studies, the restraint effect of CFST on RC plate is often neglected, and whether the RC plate will affect the bearing capacity of CFST columns. On the basis of previous studies, this paper will use the analysis software ABAQUS to research on concrete filled steel tube composite column, steel pipe in different sections under the analysis of concrete composite column behaviors and ultimate bearing capacity, for the further understanding of the compression performance and the design of this structure is calculated.

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2. Finite element modelling

2.1. Model description

2.1.1. Material properties.

For the steel tube and rebar, the plastic model with von Mises yield criterion was adopted. The elastic properties, Young's modulus and Poisson's ratio were set as measured. Uniaxial true stress-strain curve was inputted based on the formula provided in [4] for steel tubes, and bi-linear stress-strain relation assumed as E '/E=0.01 was employed for rebars. The formula suggested by Han [4] is adopted to calculate the compression strain curve for the steel-confined concrete, and concrete model provided in ACI [6] for steel reinforced concrete.

2.1.2. Material properties.

For the interaction between steel and core concrete of the CFST chord, hard contact is applied in the normal direction and the Coulomb friction model is adopted in the tangential direction, the friction coefficient is set as 0.6. Rebars is embedded to the concrete without considering the slip of the rebars in the RC connection plate.

2.1.3. Material properties.

Shell elements with reduced integration (S4R) are employed for the steel tube, whilst solid elements with reduced integration (C3D8R) are used for the core concrete of CFST columns and concrete of the RC connection plate, and 2-node linear 3-D truss element (T3D2) are adopted for the rebars in the RC connection plate. A proper mesh is chosen to achieve a balance between the computational accuracy and speed, the typical mesh is shown in Fig. 1.

2.1.4. Material properties.

On the basis of the test set-up, boundary conditions were applied to the model in the initial step as follows. The axial pressure is applied to the rigid end plate on the top of the specimen, and a fixed boundary condition is applied to the rigid end plate at the bottom of the specimen.

2.2. Verification of FEA model

In order to verify the finite element model, seven specimens tested by Chen et al. [3] are calculated. The main parameters of the test were the thickness of the steel tube and the thickness of the connection plate, the details of the specimens were shown in Table 1, where D, t and f_y are the diameter, thickness and yield strength of CFST column of the specimens respectively, h is the thickness of RC connecting plate. Fig. 1 gives a schematic view of the FEA model of the specimens (CFST-RC-2-1), and the reinforcement of the section was shown in Fig. 2.

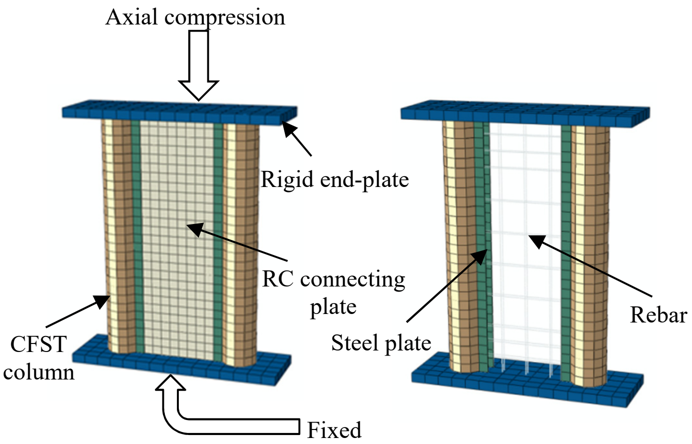


Figure 1 A schematic view of the FEA model of specimen tested by Chen et al. [3] (CFST-RC-2-1)

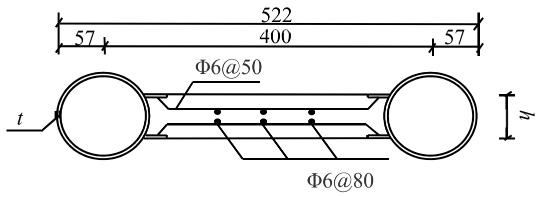
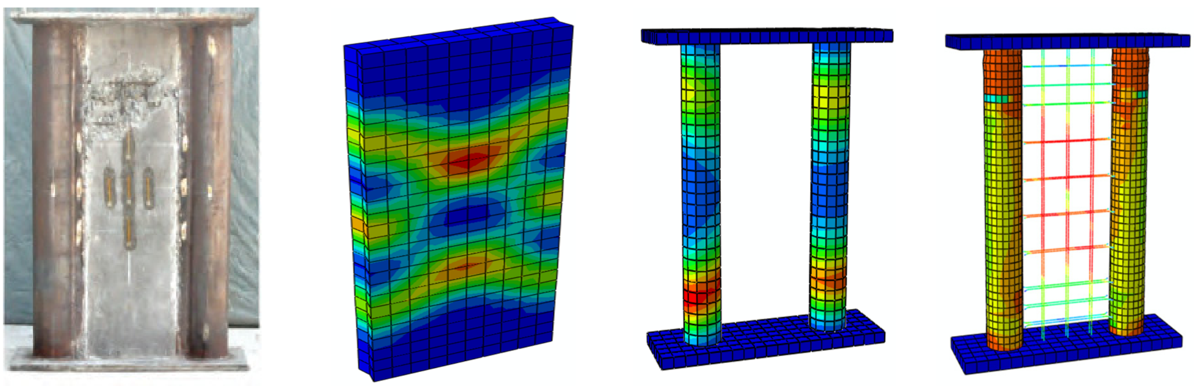


Figure 2 Section of the specimen (CFST-RC-2-1)

Table 1 Summary of test information of reference [3]

Serial number	Sample number	Thickness of steel tube $D\times t$/mm	Yield strength of steel tube f_y/MPa	Thickness of RC slab h/mm	N_{ue}/kN	N_{uc}/kN	N_{uc}/N_{ue}
1	CFST-RC-1-1	114×1.11	361	40	/	1496	/
2	CFST-RC-2-1	114×1.88	412	40	1742	1747	1.002
3	CFST-RC-3-1	114×3.03	409	40	1998	2054	1.028
4	CFST-RC-4-1	114×3.86	379	40	2168	2207	1.017
5	CFST-RC-2-2	114×1.88	412	80	1967	1841	0.935
6	CFST-RC-1-3	114×1.11	361	114	2170	2082	0.959
7	CFST-RC-2-3	114×1.88	412	114	2325	2350	1.01

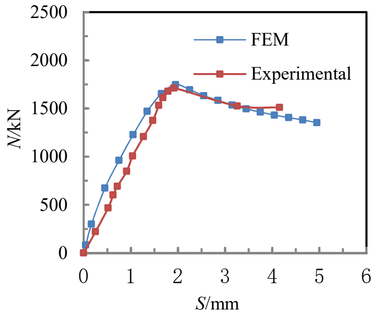
The failure modes of all CFST hybrid columns can be characterized as compression failure of RC connect plate, whole of the specimen shows the axial compression deformation, obvious local buckling was observed at the end of each column. As the failure mode of each specimen is similar, taking specimen CFST-RC-2-1 for example, the experimental observation is showed in Fig. 2(a), using the FEA model, a similar failure mode, shown in Fig. 3 (b-d), was predicted.



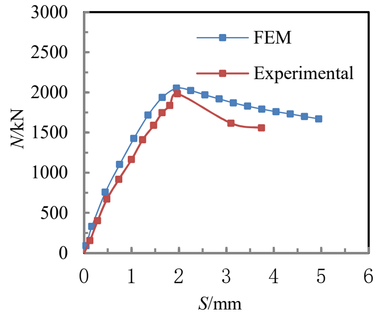
(a) Experimental observation (b) Prediction of RC connecting plate (c) Prediction of concrete in CFST column (d) Prediction of steel tube in CFST column

Figure 3 Comparison of tested and predicted failure modes (CFST-RC-2-1)

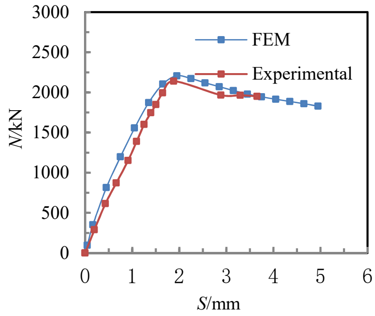
Except for specimen CFST-RC-1-1, the predicted load (*N*)-axial deformation (*S*) curves of are compared with experimental results in Fig. 4, the peak load of all specimens was showed in Table 1, where N_{ue} and N_{uc} are experimental and numerical peak load respectively Generally, the shape of the curves, the ultimate strength, the initial stiffness obtained from the present analysis is in good agreement with those of the measured results.



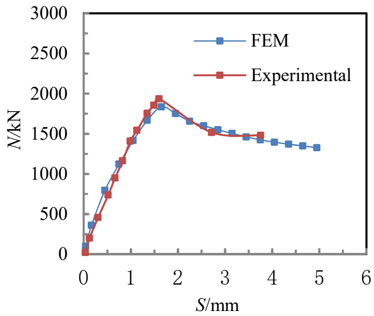
(a) CFST-RC-2-1



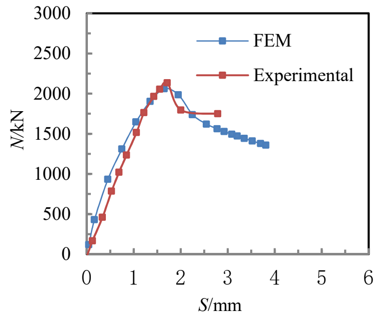
(b) CFST-RC-3-1



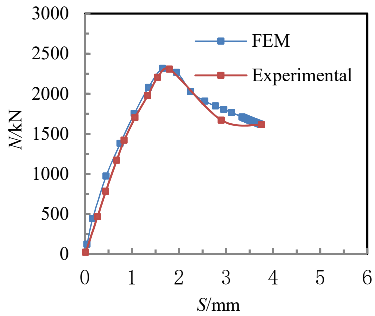
(c) CFST-RC-4-1



(d) CFST-RC-2-2



(e) CFST-RC-1-3



(f) CFST-RC-2-3

Figure 4 Load - axial displacement curve

3. Mechanism analysis

In order to analyze the failure mechanism of the CFST hybrid short column under axial compression and the strain of its cross section on the cracking load, selecting the test piece CFST-RC-2-2 whose stress and strain of each part under the cracking load, the peak load and the failure load (the peak load 85%) are analyzed, thus providing the basis for calculating the bearing capacity of composite concrete filled steel tubular short columns calculation.

3.1. Load - deformation curves

The whole process curve for the specimen CFST-RC-2-2 finite element calculation have been shown in Fig.5, the figure A expressed as RC connecting plate cracking. When the load of the specimen is up to 230.11kN, the concrete filled steel tube column limb is still in elastic stage, but at the bottom of RC connecting plate appears the plastic deformation, determining the cracking of RC connecting plate; B table shows the column the column yield. When the load of the specimen is up to 1078.41kN, the RC connecting plate cracking resulting in connecting plate stress redistribution, the distribution of steel stress increases rapidly, while the tubes began to enter the plastic section, so defining the point of the specimen yield point; C expressed as RC connecting plate steel yield distribution test. When the load of the specimen is up to 1078.41kN, the specimen reaches its peak load, CFST has yet to yield, but the yield distribution of reinforced connecting plate, resulting in the bearing capacity of specimens does not rise to yield so as to RC connection plate steel distribution To define the limit state of the specimen. D said as the specimen, test load *N*=1567kN, the load is reduced to 85% of the peak load, specimen RC connecting plate crushed, steel tube yield.

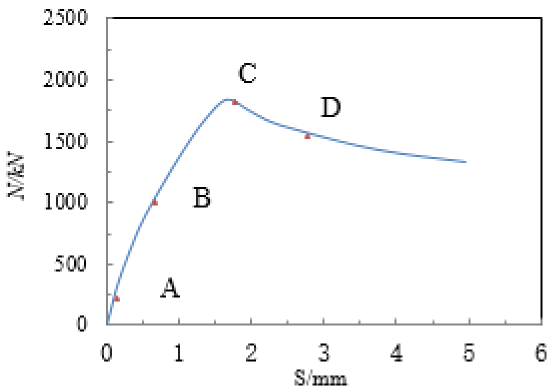


Figure 5 Full curve of CFST-RC-2-2

3.2. Distribution of the strain

Fig.6 shows the distribution chart of specimen cross section strain along the height of cross section before the peak load is reached. In the finite element model, due to the common node modelling between the concrete batten, the connecting steel plate and the steel pipe, the composite section can achieve complete deformation in the whole loading process. It also indicates that as long as the corresponding measures taken in the actual engineering can ensure that the slip between the plate and the outer wall of the steel tube is small enough, the composite section of the structure can satisfy the assumption of plane section. At the same time, when the load reaches the peak point, the strain of the steel pipe of the column limb is close to 0.002, which is consistent with the phenomenon described in the literature [3].

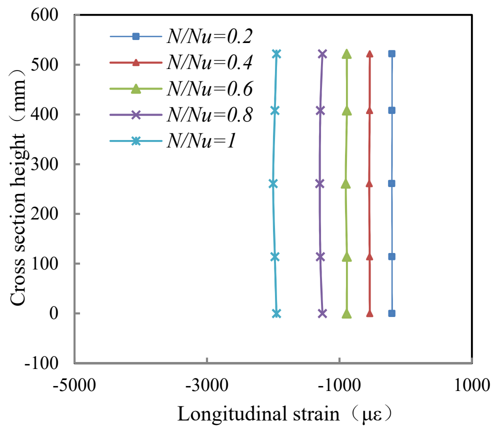


Figure 6 The change of longitudinal strain along section height

Table 2 Bearing capacity of each part of the specimen

Sample number	Thickness of steel tube t/mm	N_{uc0} /kN	N_{uc} /kN	N_{uc1} /kN	Thickness of RC slab *b*/mm	N_{uR0} /kN	N_{uR} /kN	N_{uR1} /kN
CFST-RC-1-1	1	525	607	505	40	514	605	483
CFST-RC-2-1	2	657	710	631	40	515	605	483
CFST-RC-3-1	3	830	952	783	40	515	605	485
CFST-RC-4-1	4	920	1095	858	40	516	605	486
CFST-RC-1-2	1	525	607	470	80	1105	854	746
CFST-RC-2-2	2	657	710	557	80	1105	854	834
CFST-RC-3-2	3	830	952	813	80	1105	854	779
CFST-RC-4-2	4	920	1095	810	80	1105	854	760

CFST-RC-1-3	1	525	607	495	114	1320	1130	1091
CFST-RC-2-3	2	657	710	630	114	1320	1130	1095
CFST-RC-3-3	3	830	952	797	114	1320	1130	1089
CFST-RC-4-3	4	920	1095	854	114	1320	1130	1094

N_{uc0} is the ultimate bearing capacity of the single leg concrete filled steel tube in the finite element. N_{uc} is the theoretical calculation value of the axial compression bearing capacity of the single leg concrete-filled steel tube, the N'_{UC} is the reduced column bearing capacity, and the Nuc1 is the load for the concrete filled steel tubular column when the composite column reaches the peak value.

N_{uR0} is the ultimate bearing capacity of RC connection plate in finite element analysis. N_{uR} is the theoretical calculation value of axial load capacity of RC connection plate, and Nu_{R1} is the load of RC connection plate when the composite column reaches the peak value.

For the calculation method of axial compression bearing capacity of single leg concrete filled steel tube, refer to document [8], RC formula of axial load capacity of connecting plate is referenced to document [9], and CFST stability factor of column limb is 1 because of RC connection plate.

4. Parameter analyses

In order to analyze the mechanical characteristics of the CFST hybrid columns, the thickness of the steel tube and the RC joint plate are selected as the typical parameters. The thickness of steel tube is 1~4mm, and the thickness of RC connection plate is 40mm, 80mm, 114mm (equal to the diameter of a column).

4.1. The influence of the bearing capacity of the column limb

The load - deformation curves of members with different thickness of steel tube is shown in Fig. 7. It can be seen that the increase of the steel tube thickness (t), which means the increase of bearing capacity of the CFST column, advanced the elastoplastic stage of the member. Under the same thickness of RC connecting plate, with the increase of bearing capacity of columns, the initial elastic stiffness of members is increased, and the increasement is much slight for the member with a higher bearing capacity of the column. During the descending stage, all specimens showed good ductility, which indicated that after the specimen reached peak load, most of the vertical loads were carried by the CFST column due to the removal of the RC connecting plate. The ultimate strength of the CFST hybrid column was also increased when the bearing capacity of the CFST column increased, such as when the RC connecting plate thickness is 40mm, the ultimate strength increased 14.4% when t increase from 1mm to 2mm, and the peak load of CFST hybrid column with t=3mm is 12.6% higher than that of CFST hybrid column with t=2mm. However, load-bearing capacity of CFST hybrid column with t=4mm increased less than 10% than that of member with t=3mm, which indicates that the influence of load-bearing capacity of the CFST column has a limit. At the same time, according to the calculation results of bearing capacity of concrete filled steel tubular columns and concrete slabs in Table 2, it can be seen that the bearing capacity of the single CFST column should not exceed 60% of the bearing capacity of the RC connecting plate.

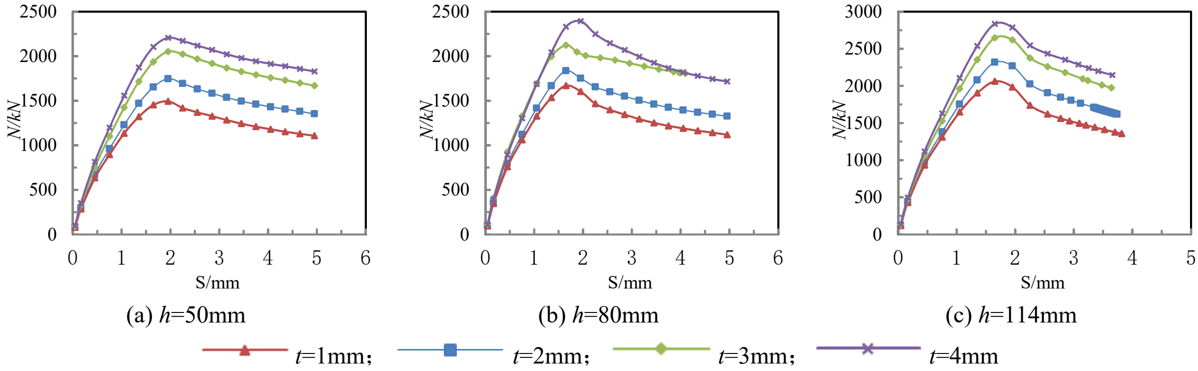


Figure 7 The influence of the thickness of steel tube on the load-deformation curve

4.2. Influence of RC connecting plate

The load - deformation curves of members with different thickness of RC connecting plate is shown in Fig. 8. When the thickness of RC connecting plate (*h*) increased, the overall stiffness and load-bearing capacity of the CFST hybrid column has been improved, but it also makes hybrid column get into the plastic stage much early at the same time. And after reaching the peak load, the RC connection plate occupies a larger proportion on the whole compression section, which makes the descending trend of the members similar to the reinforced concrete structure, the stiffness degradation is more obvious, and the ductility is worse. When the bearing capacity is reduced to a certain extent, the RC connection plate is out of work, and the main vertical load of the CFST part of the column limb is assumed, so the later ductility of the specimen shows better. Based on a great deal of calculation and analysis, the CFST hybrid column has better ductility when the area of the RC connection plate less than 50% of the section of whole member.

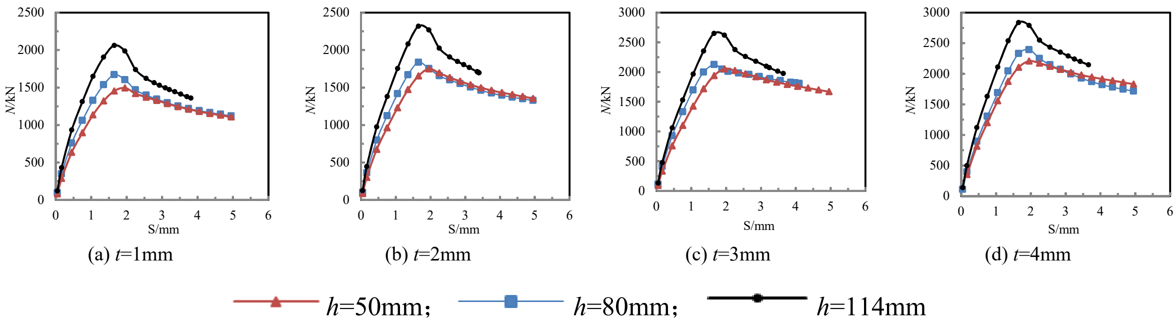


Figure 8 Effect of thickness of RC plate on load displacement curve

5. Conclusion

1) The finite element method is used to simulate the mechanical properties of the CFST hybrid column and the result of finite element calculation is in good agreement with the test result.

2) The distribution of the strain of the composite section before the peak load of the specimen is given along the height of the cross section, and it is determined that the specimen will conform to the assumption of the flat section before the peak load is reached.

3) The CFST hybrid column has solved the problem of instability of column legs under the action of RC connection plate, and the peak load of such structure is mainly determined by the bearing capacity of RC connection plate. The concrete filled steel tube makes the structure better ductility after the peak load is reached. Through finite element calculation, it is suggested that the bearing capacity of concrete-filled steel tubular column should not exceed 60% of the RC connection plate's bearing capacity, and the area of the RC connection plate's compression section is not higher than that of the column steel tube concrete section area 50%.

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References
[1] Huang Y, Briseghella B, Zordan T, Wu Q, & Chen B 2014 Shaking table tests for the evaluation of the seismic performance of an innovative lightweight bridge with cfst composite truss girder and lattice pier Engineering Structures 75(9) 73
[2] Chen B C and Wang T L 2009 Overview of concrete filled steel tube arch bridges in china Practice Periodical on Structural Design & Construction 14(2) 70
[3] Chen B C, Yan Q L and Xue J Y 2016 Experimental study on axial compression performance of CFST hybird short columns Journal of architectural structure 37 (5) 82
[4] Yan Q L, Chen B C, Xue J Y 2013 The reduction factor of bearing capacity of CFST hybrid short columns Journal of building structures 2 34 (Supplement 1) 294
[5] Han L H 2007 Concrete-filled steel tube structure: Theory and practice (Beijing Science: Press)
[6] Attard M M，Setunge S 1996 Stress-strain relationship of confined and unconfined concrete ACI Materials Journal 93(5) 432
[7] Guo X D 2007 When principle and analysis of reinforced concrete (Beijing: Tsinghua University press)
[8] Liu W 2005 Study on the working mechanism of local compression of concrete filled steel tube (Fuzhou: Fuzhou University)
[9] GB 50936-2014 2014 Technical specification for concrete filled steel tube structure (Beijing: China Construction Industry Press)
[10] GB 50010-2010 Specification for design of concrete structure (Beijing: China Construction Industry Press)