Finite Element Analysis and Verification on Hollow Concrete Filled Double Steel Tube Short Columns Subjected to Axial Load

Ming Xu¹, Zhanfeng Song², Li Jiang³, Jing Ji³* and Huayu Song³
¹Department of Architectural Engineering, Qiqihar Institute of Engineering, Qiqihar, Heilongjiang, 161005, China
²Jilin Petrochemical Mining Area Service Department of PetroChina, Jilin, 132000, China
³College of Civil and Architectural Engineering, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China
*Corresponding author’s e-mail: jjjing1977@163.com

Abstract: In order to study the axial compression behavior of hollow concrete filled double steel tube (HCFST) short columns, the finite element numerical simulation of five existing short columns under axial compression is carried out by ABAQUS. By choosing reasonable material constitutive model, the finite element model of this kind of short column is established, and the load-displacement curve of hollow concrete filled double steel tube short column is obtained by simulation analysis. Compared with the existing test results, the simulation data is in good agreement with the test results. The rationality and practicability of the finite element modeling method in this paper are verified. It also lays a theoretical foundation for the popularization and application of hollow concrete filled steel tube short columns in practical engineering.

1. Introduction
With the development of architectural structure system heading for large span and large space, attentions also have been paid to the appearance of architectural structure. The structural system of conventional concrete filled steel tube columns has a large self-weight, and it will spend lots of concrete. In order to save materials, some new structural forms have appeared on the basis of the original concrete filled steel tube structure. J Ji investigated the influence of post-fire curing methods on the mechanical properties of fire-damaged ultra-high toughness cementitious composites (UHTCC)[1]. The nonlinear analysis on the overall stability of H-type honeycombed composite column with rectangular concrete-filled steel tube flanges was carried out by J Ji[2]. In the paper, hollow concrete filled double steel tube short column is one of the new structure forms. Its structural form is to place two layers of steel tube concentrically together, and pour concrete between the holes of the two layers of steel tube. This composite structure not only saves the usage of concrete and reduces the self-weight of the structure, but also enhances the bending stiffness and seismic behaviour of the structure. But the research about this kind of hollow concrete filled double steel tube short columns is not perfect now. With the help of the finite element software ABAQUS[3] in this article, the finite element model of hollow concrete filled steel tube short columns is established by choosing reasonable material constitutive model, and the load-displacement curves of the hollow concrete filled double steel tube short columns are obtained. Compared with the
curves of experimental data, the rationality of finite element modelling is verified in this article. These can lay a theoretical foundation for the popularization and application of such short columns in practical engineering.

2. Material and methods

2.1 General situation of existing experiments

In order to prove the rationality of the finite element model of HCFST short columns, numerical simulation analysis are carried out for five test specimens which L H Han has finished. The specific parameters of the specimens are shown in table 1. Specimen cc1b is a common concrete filled steel tube column. $h$ is the height of specimens. $t_i$ and $t_o$ stand for the thickness of inner and outer tubes, respectively. $D_o$ and $D_i$ stand for the diameter of inner and outer tubes. $f_{yi}$ and $f_{yo}$ stand for the strength of inner and outer tubes.

| Specimen | $h$/mm | $t_i$/mm | $t_o$/mm | $D_o$/mm | $D_i$/mm | $f_{yi}$/MPa | $f_{yo}$/MPa |
|----------|--------|----------|----------|----------|----------|-------------|-------------|
| cc1b     | 540    | -        | 33       | 4        | 180      | -           | 275.9       |
| cc2b     | 540    | 3        | 33       | 4        | 180      | 48          | 396.1       |
| cc3a     | 540    | 3        | 33       | 4        | 180      | 88          | 370.2       |
| cc4a     | 540    | 3        | 33       | 4        | 180      | 140         | 342.0       |
| cc5a     | 342    | 3        | 33       | 5        | 114      | 58          | 374.5       | 295.4       |

2.2 Constitutive model of materials

2.2.1. Constitutive model of steel materials. Steel tube is made of bilinear ideal elastic-plastic model, which is shown in figure 1. This model is divided into two stages: elastic rising stage and hardening stage. Because of the transverse support between concrete and steel tube, the buckling deformation of steel tubes is effectively delayed or avoided, the axial allowable strain of steel tube is obviously increased. The circumferential tensile properties are fully developed. So hardening effect should be considered when steel pipe reaches the yield point. Equation (1) is the constitutive relation expression of steel tube.

$$
\sigma_i = \begin{cases} 
E_i \times \varepsilon & \varepsilon \leq \varepsilon_{y_i} \\
 f_{yi} + E_i \times \left[ \varepsilon - \varepsilon_{y_i} \right] & \varepsilon > \varepsilon_{y_i}
\end{cases}
$$

Where: $E_i$ is the elastic modulus of steel tube. $E_1$ is the stiffness coefficient when steel tube is in the hardening stage. $E_1$ is equal to $0.01E_i[4]$. $f_{yi}$ is the radial ultimate tensile strength of steel tube. $\varepsilon_{y_i}$ is the corresponding strain values of steel tube.

![Stress-strain curve of steel tube.](image)
2.2.2 Constitutive model of concrete. In the process of choosing the concrete’s stress-strain relationship of HCFST short columns in this article, we arranged constitutive model of confined concrete proposed by L H Han[5], M Pagoulatou[6], J B Mander[7], J G Teng[8] and constitutive model of unconstrained concrete(CM) proposed by GB50010-2010[9] in China. The contrast curves are shown in figure 2.

![Figure 2. Nonlinear Constitutive Model of Concrete.](image)

2.3 Establishment of finite element model
Inner and outer steel tubes and concrete of hollow concrete filled double steel tube short columns all use eight-node and three-dimensional solid element, the cross-section contact mode of steel tube and concrete is global universal contact, namely "hard" contact on normal direction and friction contact considering relative bond slip on tangent direction. Bind upper and lower backing plate and plane of the column together, then exert displacement load on top of upper backing plate, and let the load transfer through the backing plate to act on the upper surface of the whole specimen. The e bottom of the backing plate is fixed[10].

2.4 Selection of material constitutive model
By simulating the process of specimen cc5a under axial pressure in this paper, the load-displacement curves of specimen cc5a based on different constitutive models are obtained. We can know that it is reasonable to use the constitutive model proposed by L. H. Han to launch the finite element simulation analysis of such components through the comparison between the five curves in figure 3.

The stress-strain relationship of concrete is as follows:

\[
\xi = \frac{A_c}{A} \left( \frac{A_{ty} f_y}{A_{ty} f_y + A_{oy} f_0} \right) + \frac{A_{oy} f_0}{A_{oy} f_y + A_{oy} f_0} \quad (x \leq 1)
\]

\[
y = \frac{2x - x^2}{\beta_0 \left(x - 1\right)^{\frac{1+\xi_0}{\xi_0}}} + x \quad (x > 1)
\]

Where: \(x = \frac{\varepsilon}{\varepsilon_0^0} \); \(y = \frac{\sigma}{\sigma_0} \); \(\delta_0 = f_y \); \(\varepsilon_0 = (1300 + 12.5 f_y) \times 10^{-6} + 800 \cdot \xi_0^0 \cdot 10^{-6} \). \(\sigma_0 \) is the peak value of compressive stress. \(\varepsilon_0 \) is the corresponding peak value of compressive strain. \(A_c, A_t \) and \(A_o \) is full section area, concrete section area and steel tube section area of HCFST short column (i stands for the inner layer, o stands for the outer layer). \(f_y \) is design value of ultimate bearing capacity of steel tube. \(f_{ck} \) is standard value of ultimate bearing capacity of concrete.

\[
y = \begin{cases} 
1.2 \times x - 0.2 \times x^6 & (x < 1) \\
\frac{x}{0.31\sigma_0^2 \left(x - 1\right)^7} + x & (x > 1) 
\end{cases}
\]
Where: $x = \varepsilon_p \sigma_p$; $y = \varepsilon_p \sigma_p$; $\sigma_p$ is the peak value of stress. $\varepsilon_p$ is the strain corresponding to the corresponding peak point. Specific expressions is shown in (5, 6):

$$\sigma_p = 0.26 \times \left(1.25 \times f_c\right)^{2/3} \quad (5)$$

$$\varepsilon_p = 43.1 \times \sigma_p \left(\mu \varepsilon\right) \quad (6)$$

Figure 3. Load-displacement curves of specimen cc5a under different concrete constitutive models.

3. Finite element results

Five specimens were simulated and analyzed by the above finite element modeling method, the load-displacement curves of specimens are shown in figure 4.

![Load-displacement curves](image)

(a) Specimen cc1b  (b) Specimen cc2b  (c) Specimen cc3a  
(d) Specimen cc4a  (e) Specimen cc5a

Figure 4. Comparison between finite element method and test results.

In addition to the comparison of load-displacement curves, the comparison of ultimate bearing capacity of specimens can also verify the rationality of finite element model ABAQUS. Table 2 is the results of the bearing capacity of five specimens under different parameters.
Table 2. Comparison between simulation and test results of existing specimens.

| Specimen | Constrained effect coefficient ξ | Hollow rate T | Simulated bearing capacity N_s | Test bearing capacity N_t |
|----------|----------------------------------|---------------|-----------------------------|------------------------|
| cc1b     | 0.76                             | 0.00          | 1701.29                     | 1665.71                |
| cc2b     | 0.83                             | 0.09          | 1825.84                     | 1807.42                |
| cc3a     | 1.04                             | 0.27          | 1516.71                     | 1402.58                |
| cc4a     | 2.22                             | 0.66          | 1702.31                     | 1680.42                |
| cc5a     | 2.39                             | 0.32          | 1602.81                     | 1752.49                |

According to figure 3 and table 2, five existing specimens were simulated and verified by ABAQUS software on the premise of adopting reasonable constitutive model. Compared the analysis results with the test data, the rationality and the correctness of finite element simulation is verified.

4. Conclusions

Based on finite element software ABAQUS, the axial compression performance of hollow steel tubular short columns is simulated. By selecting a reasonable constitutive model, five existing specimens are analyzed and the load-displacement curves of hollow steel tubular short columns are obtained. The analysis results are compared with the experimental data, and the results are in good agreement. The correctness of the finite element simulation is verified.

Acknowledgments

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