Finite Element Analysis and Experimental Verification on Joint with CFST Columns and Unequal Height Steel Beams

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Abstract. In order to study the mechanical properties of joints with CFST columns and unequal height steel beams, based on the simplified mechanical model and reasonable material constitutive model, the finite element model of this kind of joints is established by using ABAQUS finite element software, and four joints are simulated and analyzed and the load-displacement hysteretic curves and skeleton curves of the specimens are obtained. The results show that the hysteretic curves of this kind of joints are relatively full, and it has strong energy consumption capacity. Comparing the simulated hysteretic and skeleton curves with the existing test results, the two are in good agreement, which verifies the rationality and feasibility of the finite element modelling. Finally, the seismic strengthening measures of this kind of joint are given, which lays the foundation for the subsequent research on the seismic performance of the frame with this kind of joint.

1. Introduction

In recent decades, with the advantages of high strength, heat resistance and convenient construction, concrete-filled steel tubular composite structure has entered the construction market. The conventional composite structure can not meet the growing demand, and the market has a greater demand for unequal height beam joints. Concrete filled steel tubular column has better toughness and plasticity and better bearing capacity when encountering earthquake, while H-shaped steel beam is easier to enter into plastic stage when encountering earthquake. Both of them just meet the principle of strong column and weak beam, which makes concrete-filled steel tube-H shaped steel beam joint have strong energy dissipation capacity subjected to cyclic load. Considering practical and economic factors, it is often necessary for steel beams with different section sizes to be used on both sides of the column. Due to the special form of unequal sorghum, it is necessary to study and discuss its mechanical characteristics further.

At the end of 1980s, scholars at home and abroad began to study the seismic behavior of concrete filled steel tubular (CFST) - steel beam joints. Z J Li [1] studied the seismic performance of the rigid joints of concrete filled steel tubular columns and steel beam frames, and gave reasonable design suggestions. Based on the finite element software ABAQUS, J F Wang[2] studied the mechanical performance of square steel tubular column steel beam joint with external strong ring, obtained the load deformation whole process curve and skeleton curve, and put forward reasonable ring plate width design suggestions. Based on ANSYS software, Q Y Shi[3] and others used the simplified Varma...
model as the cyclic constitutive model of steel, and analyzed the hysteretic behavior of the joint between concrete-filled steel tubular column and composite beam. The results show that in the core area of the joint, the beam negative reinforcement through the steel tube and the reinforcement ring are beneficial to the seismic performance of the joint. Based on ABAQUS, Y S Su[4] studied the influence of reinforcement ring on seismic performance of square steel tube recycled concrete column steel beam joints. The results show that the existence of reinforcement ring can effectively limit the drum deformation of steel tube in the core area of the joint, and can improve the seismic bearing capacity of the joint. In order to study the seismic performance of concrete-filled steel tubular column-H shaped unequal height steel beam joints, four joint models were made for loading test by C X Xu [5]. The results show that the failure of joints starts from the beam end, and the core area has no damage, which meets the requirements of strong joint and weak member, the hysteresis curve pinch is obvious, and the overall construction has good energy dissipation capacity. Based on OPENSEES software, the numerical model of this kind of joint is established [6], and the numerical simulation analysis is carried out. The research results show that the greater the steel pipe strength, the greater the ultimate bearing capacity and ductility of the joint, and the improvement of concrete strength grade has little impact on the bearing capacity of the joint.

Based on ABAQUS finite element software, the finite element model of CFST column unequal height steel beam joint is established through reasonable material constitutive relationship, simplified mechanical model, boundary conditions, meshing and loading system. The simulation analysis of CFST column unequal height steel beam node is carried out, and the energy dissipation coefficient, hysteresis curve and skeleton curve are extracted and the ductility coefficient is compared with the experimental value, which proves the rationality of the finite element model. It lays a foundation for the subsequent research on the seismic performance of the frame with such joints.

2. Finite element model

2.1. Simplified calculation model of nodes
The simplified calculation model of CFST column unequal height steel beam joint is shown in figure 1. The end of the beam and the bottom of the column are hinged, and the displacement of the top of the column is not limited. Vertical force and periodic horizontal load are applied on the top of the column.

![Figure 1. Simplified node calculation model](image)

2.2. Material constitutive model
LH Han[7], J G Teng[8] and M Pagoulatou [9] have given the constitutive models of confined concrete, and the constitutive model of unconstrained concrete has been given in the code for design of concrete structures (GB 50010-2010) [10]. In this paper, L H Han's constitutive model is adopted, and the expression of the constitutive model of confined concrete is shown in formula (1)-(9). The
plastic damage model is adopted in the finite element modelling of concrete. The dual line constitutive model of steel considering hardening after yielding is adopted.

\[
y = \begin{cases} 
2x - x^2 & (x \leq 1) \\
\frac{x}{\beta_0(x-1)^2 + x} & (x > 1)
\end{cases}
\]  

(1)

Where:

\[
x = \frac{\varepsilon}{\varepsilon_0}; 
\]

(2)

\[
y = \frac{\sigma}{\sigma_0}; 
\]

(3)

\[
\sigma_0 = f_c(N/mm); 
\]

(4)

\[
\varepsilon_0 = \varepsilon_c + 800 \cdot \varepsilon_0^{0.2} \cdot 10^{-6}; 
\]

(5)

\[
\varepsilon_c = (1300 + 12.5 \cdot f_c) \cdot 10^{-6}; 
\]

(6)

\[
\eta = \begin{cases} 
2 & \text{(Round steel pipe)} \\
1.6 + \left(\frac{1.5}{x}\right) & \text{(Square steel pipe)}
\end{cases}
\]  

(7)

\[
\beta_0 \frac{f_c^{0.1}}{1.2 \sqrt{1 + \xi}} \begin{cases} 
(2.36 \times 10^{-5})^{0.25 + (\xi - 0.5)^2} \cdot f_c^{0.5} \cdot 0.5 \geq 0.12 & \text{(Round steel pipe)} \\
& \text{(Square steel pipe)}
\end{cases}
\]  

(8)

The expression of stress-strain relationship of concrete is as follows:

\[
y = \begin{cases} 
1.2 \cdot x - 0.2 \cdot x^6 & (x \leq 1) \\
\frac{x}{0.31 \cdot \sigma_p^2(x-1)^{1/7} + x} & (x > 1)
\end{cases}
\]  

(9)

Where, \( x = \frac{\varepsilon_c}{\varepsilon_p} \); \( y = \frac{\sigma}{\sigma_p} \), \( \sigma_p \) is the peak tensile stress, and \( \varepsilon_p \) is the tensile peak strain.

2.3. Establishment of finite element model

AB AQUS software is used to model steel pipe, steel beam and concrete. A geometry model is created as shown in figure2. The properties of steel and concrete are established according to the above constitutive model. The contact effect between concrete and steel pipe is simplified as normal hard contact and tangential frictional contact. Appropriate load and boundary conditions are set according to the loading device. MPC is used to constrain the hinge type inside the beam end to limit the vertical displacement and simulate the sliding connection without any load. The axial pressure on the top surface is applied on the top of the column in the first and second analysis steps, and the horizontal cyclic load is applied in the second analysis step without any constraint. The MPC constraint is applied to the bottom of the column, and the MPC type is also used to constrain the displacement in X.
and Z directions. After comparison, it is found that the grid of 50mm is the most consistent with the test value. Grid division is shown in figure 3.

![Figure 2. geometry model of joint](image)
![Figure 3. grid meshing of joint](image)

3. Experimental verification of finite element simulation

3.1. Overview of existing tests

The specific parameters of the four existing specimens are shown in table 1. The strength grade of concrete in square steel tube is C40. Q235 steel is used as steel tube, and the yield stress and ultimate stress of steel tube are 307 MPa and 419 MPa, respectively. The yield stress and ultimate stress of steel beam are 324 MPa and 439 MPa, respectively.

| Specimen | Higher beams (mm$^4$) | Lower beam (mm$^4$) | CFST column (mm$^3$) | Concrete strength grade | Axial compression ratio |
|----------|------------------------|----------------------|----------------------|------------------------|------------------------|
| CFSTJ-1  | 280×100×6×8            | 80×100×6×8           | 200×200×6            | C40                    | 0.4                    |
| CFSTJ-2  | 130×100×6×8            | 180×100×6×8          |                      |                        |                        |
| CFSTJ-3  | 180×100×6×8            |                      |                      |                        |                        |
| CFSTJ-4  | 230×100×6×8            |                      |                      |                        |                        |

3.2. Finite element results and comparison

The hysteretic curves and skeleton curves of the four specimens were obtained by using the above method as shown in figure 4 and figure 5. The simulated ultimate bearing capacity data of the specimens are shown in Table 2. Comparing the average value of ultimate bearing capacity obtained from the test with the average value of ultimate bearing capacity obtained by simulation, the error is within 10%, which proves the accuracy of the simulation data and the rationality of the model. From the comparison of test and simulation skeleton curves, it can be seen that stiffness degradation and bearing capacity decrease after yielding. From the comparison of skeleton curves, it can be seen that the ultimate bearing capacity of test and finite element curves are similar, which verifies the rationality of the finite element model. At the same time, the initial stiffness of the finite element simulation curve is larger than that of the test curves, and the pinch shrinkage is not obvious, which is due to the fact that the bond slip is not considered in the simulation. In the elastic stage, two curves are in good agreement, but in the plastic stage, the agreement is general, which may be due to the fact that the concrete is regarded as a continuous and isotropic element, but it is actually a discrete element.
Figure 4. Comparison of hysteresis curves between simulation and test

Figure 5. Comparison of skeleton curves between simulation and test
Table 2. Comparison of bearing capacity between simulation and test

| Specimens | $N_t^+$ (kN) | $N_t$ (kN) | $\bar{N}_t$ (kN) | $N_s^+$ (kN) | $N_s$ (kN) | $\bar{N}_s$ (kN) | $\frac{N_t - \bar{N}_t}{N_t} \times 100\%$ |
|-----------|--------------|-----------|----------------|--------------|------------|----------------|-------------------------------|
| CFSTJ-1   | 157.20       | -150.62   | 153.91         | 149.23       | -155.40    | 152.32         | 1.0%                          |
| CFSTJ-2   | 158.17       | -173.20   | 165.69         | 154.98       | -155.25    | 155.15         | 6.4%                          |
| CFSTJ-3   | 165.09       | -180.02   | 172.56         | 159.93       | -158.42    | 159.18         | 7.8%                          |
| CFSTJ-4   | 176.88       | -194.39   | 185.64         | 166.63       | -167.97    | 167.30         | 9.8%                          |

4. Conclusion

ABAQUS finite element software is used to establish the joint model of concrete-filled steel tubular column and unequal height steel beams. By setting appropriate constitutive parameters of concrete and steel, the hysteretic curves and skeleton curves model of four specimens are obtained. The average value of ultimate bearing capacity of test and simulation is compared, and the error is small, which proves the rationality of the simulation. It lays a foundation for the subsequent research on the seismic performance of the frame with such joints.

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