Finite Element Analysis on Behavior of Reinforced Hollow High Strength Concrete Filled Square Steel Tube Short Columns under Axial Compression

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Abstract. Hollow concrete-filled steel tubular (CFST) member is mainly adopted in power transmission and transformation structures, but when it is used in the superstructure with complex stress, the hollow CFST member has a low bearing capacity and is prone to brittle failure. To improve the mechanical performance of hollow CFST members, a new type of reinforced hollow high strength concrete-filled square steel tube (RHCFSST) was proposed, and its axial compression performance was researched. 18 finite element analysis (FEA) models of axially loaded RHCFSST stub columns were established through FEA software ABAQUS. The whole stress process of composite columns was studied, and parametric studies were carried out to analyze the mechanical performance of the member. Parameters of the steel strength, steel ratio, deformed bar and sandwich concrete strength were varied. Based on the simulation results, the stress process of members can be divided into four stages: elastic stage, elastoplastic stage, descending stage and gentle stage. With the increase of steel strength, steel ratio, the strength of sandwich concrete and the addition of deformed bars, the ultimate bearing capacity of members also increases. Additionally, the increment of those parameters will improve the ductility of the member, except for the sandwich concrete strength.

Keywords. Axial compression, hollow concrete filled steel tube, stress process, bearing capacity, ductility.

1. Introduction
Concrete-filled steel tubular (CFST) columns are widely applied in modern structural members of long-span structures, high-rise buildings and offshore platforms for their excellent structural characteristics such as high bearing capacity, good ductility and remarkable comprehensive benefits [1]. The hollow CFST member is prefabricated by centrifugal molding, high temperature and high-pressure steam curing in the factory, which has the advantages of avoiding wet operation on-site, shortening the construction period, saving cement consumption, and stable and reliable quality. At present, hollow CFST members have been successfully used in power transmission, substation towers and foundations [2-3].

Scholars have demonstrated that adding the reinforcement can improve the bearing capacity and ductility of CFST members. Xiamuxi et al. [4] found that the bearing capacity of reinforced CFST columns was increased, and the internal steel bars could give full play to their functions and improved their plasticity and ductility. Chen et al. [5] studied the mechanical performances of square CFST columns with spiral stirrups. The results showed that spiral stirrups can enhance the steel restraint effect on core concrete and effectively improve the bearing capacity of the member. Ding et al. [6-7] had experimentally and numerically studied the mechanical properties of concrete stub columns.
confined by steel tube stirrups with different cross-sections under axial compression. The results verified that using stirrups can reduce the local bulges of steel tubes, improve the restraining effect of the steel tube, and increase the bearing capacity. Chen [8-9] had conducted experimental tests on square CFST columns reinforced by spiral reinforcement under axially compressed load. It was found that the configuration of spiral stirrup can effectively improve the restraint effect of square steel tube on core concrete, increase the bearing capacity and deformation capacity of members, and all parts have good deformation coordination. To fully exert the advantages of hollow CFST columns, make up for its bearing capacity and improve its brittle failure, Yang et al. [10] have proposed a reinforced hollow high-strength concrete-filled steel tube (RHCFSST) column, which was a new-typed composite column formed by combining prestressed high-strength concrete pile (PHC pile) with CFST. Most of the existing research has focused on hollow CFST members or reinforced CFST members, while the research on RHCFSST columns is still less. In this paper, the finite element analysis (FEA) models were built using ABAQUS, and the axial compression performances of RHCFSST columns were studied.

2. Model Design
The finite element analysis model of 18 axially loaded RHCFSST short columns was designed. The effects of steel yield strength, sandwich concrete strength, steel ratio and deformed bars in the PHC column were investigated. The cross-sectional form of the member is displayed in figure 1, which is made up of three parts: steel tube, sandwich concrete and PHC column. The detailed parameters of the component are shown in table 1.

3. Establishment of Numerical Model

3.1. Selection of Material Constitutive Relationships
The concrete plastic damage model of ABAQUS was adopted for the concrete [11], and the concrete consists of sandwich concrete and PHC column. The compressive stress-strain relationship modified by Liu [12] was selected for core concrete, and that put forward by Guo [13] was adopt for the PHC column. The constitutive relationship for concrete under tension was expressed by fracture energy. Steel tubular and deformed bars used the constitutive relation models of the pentagonal model, prestressed reinforcement used a two-fold line model for high-strength steel [11]. The prestress of the PHC column was applied by the cooling method [14].
Table 1. Design parameters of specimens.

| Specimen Number | t/mm | $f_y$/MPa | Stirrup $^a$ /mm | Prestressed tendon $^c$/mm | Deformed bar $^d$/mm | $f_{yd}$/MPa | $N_u$/kN |
|-----------------|------|-----------|-----------------|---------------------------|---------------------|-------------|----------|
| RHCFSST-1       | 6    | 235       | Φ4@45          | 6Φ10.7                    | 60                  | 8773        |
| RHCFSST-2       | 6    | 390       | Φ4@45          | 6Φ10.7                    | 80                  | 11310       |
| RHCFSST-3       | 6    | 460       | Φ4@45          | 6Φ10.7                    | 80                  | 11683       |
| RHCFSST-4       | 6    | 550       | Φ4@45          | 6Φ10.7                    | 80                  | 11796       |
| RHCFSST-5       | 6    | 690       | Φ4@45          | 6Φ10.7                    | 80                  | 12409       |
| RHCFSST-6       | 6    | 235       | Φ4@45          | 6Φ10.7                    | 70                  | 9097        |
| RHCFSST-7       | 6    | 235       | Φ4@45          | 6Φ10.7                    | 80                  | 10336       |
| RHCFSST-8       | 6    | 235       | Φ4@45          | 6Φ10.7                    | 90                  | 10340       |
| RHCFSST-9       | 6    | 235       | Φ4@45          | 6Φ10.7                    | 100                 | 11059       |
| RHCFSST-10      | 5    | 235       | Φ4@45          | 6Φ10.7                    | 80                  | 9578        |
| RHCFSST-11      | 8    | 235       | Φ4@45          | 6Φ10.7                    | 80                  | 10480       |
| RHCFSST-12      | 10   | 235       | Φ4@45          | 6Φ10.7                    | 80                  | 11006       |
| RHCFSST-13      | 12   | 235       | Φ4@45          | 6Φ10.7                    | 80                  | 11420       |
| RHCFSST-14      | 5    | 235       | Φ4@45          | 6Φ10.7                    | 60                  | 8495        |
| RHCFSST-15      | 5    | 235       | Φ4@45          | 6Φ10.7                    | 6Φ16                | 60          | 8994      |
| RHCFSST-16      | 6    | 235       | Φ4@45          | 6Φ10.7                    | 6Φ16                | 60          | 9273      |
| RHCFSST-17      | 8    | 235       | Φ4@45          | 6Φ10.7                    | 6Φ16                | 60          | 9282      |
| RHCFSST-18      | 8    | 235       | Φ4@45          | 6Φ10.7                    | 6Φ16                | 60          | 9822      |

a. The length of the designed member ($L$) is 1200 mm, the diameter of square steel tube ($D$) is 400 mm, the outer diameter of PHC column ($D_{pc}$) is 300 mm with the wall thickness ($d_l$) is 70 mm, and the compressive strength of PHC column concrete ($f_{ck}$) is 80MPa.

b. The stirrup strength ($f_{ys}$) is 650 MPa.

c. The tensile strength of prestressed tendon ($f_{pyk}$) is 1420 MPa, the distribution circle diameter of prestressed tendon ($D_{pc}$) is 230mm.

d. The yield strength of deformed bars ($f_{yd}$) is 400 MPa.

3.2. Establishment of FEA Model

The FEA model of RHCFSST is exhibited in figure 2. C3D8R element was utilized for the endplate, steel tube, sandwich concrete and PHC column, and T3D2 element was used for prestressed tendon, stirrup and deformed bars. “Hard contact” was adopted for the interface between steel tube and concrete in the normal direction, and the Coulomb friction model provided by ABAQUS was used for tangential interaction with the interface friction coefficient of 0.6 [15]. “Hard contact” was adopted to model the contact of concrete and endplate. The sandwich concrete and PHC column, and endplate and steel tube were tied together. The stirrup, prestressed tendon and deformed bars were directly “embedded” into concrete. The load was applied by displacement.

4. Results of Finite Element Analysis

Figure 3 displays the load-displacement curve of a typical RHCFSST short column under axial compression. From this, the loading process of the RHCFSST-1 column can be split into four stages.

Elastic stage (OA): At this stage, each component of the model bears the load independently, and the model has no significant deformation. Point A is the last point of the elastic section when the steel tube reaches the yield strength.
Elastic-plastic stage (AB): At this stage, the micro-cracks of concrete continue to expand, except for prestressed tendons and stirrups, the rest of the material all produce plastic strain, the PHC column reaches its ultimate bearing capacity. The pre-tensile stress of prestressed tendons gradually decreases, and prestressed tendons enter a compression state. When it reaches point B, the sandwich concrete reaches ultimate bearing capacity, and the RHCFSST-1 column also reaches ultimate bearing capacity.

Descending stage (BC): At this stage, both the PHC column concrete and the sandwich concrete reach their ultimate compressive strain, the concrete is crushed, and the bearing capacity continues to decline. The stress of prestressed tendons gradually increases, and it reaches its yield strength at the end of the descending stage (point C). The steel tube bulges and the constraint on the sandwich concrete gradually weakens.

Gentle stage (CD): At this stage, serious damage has been observed in the concrete and the steel tube. Due to the existence of prestressed tendons and stirrups, each component of the member is more stable which indicates the load-displacement curve enters a gentle stage.

5. Parameter Analysis

5.1. Wall Thickness of Steel Tube
Figure 4 is the load-displacement curve of members with various thicknesses of the steel tube. In the elastic stage, the initial stiffness rises with the increasing steel ratio, and the ultimate bearing capacity of composite columns increased by 7.9%, 9.1%, 14.9% and 19.2%, respectively. The descending trend slows down obviously, and the ductility increases slightly.

Figure 2. Establishment of model.

Figure 3. Load-displacement curves of RHCFSST-1.

Figure 4. Load-displacement curve under the influence of steel tube wall thickness.
5.2. Steel Yield Strength

Figure 5 exhibits the load-displacement curve of members with different steel yield strengths. With the increasing steel yield strength, the initial stiffness of members has no obvious change. When the steel yield strength increases from 235 MPa to 690 MPa, the bearing capacity of each member increases by 14.2%, 13.6%, 10.4% and 10.6%, respectively, whose increment rate is huge, the descending section slows down, and the ductility improves obviously.

![Figure 5. Load-displacement curve under the influence of steel tube strength.](image)

5.3. Sandwich Concrete Strength

Figure 6 displays the load-displacement curve of members with the concrete strength as variables. The ultimate bearing capacity of composite columns raised by 3.7%, 17.8%, 17.9% and 26.1% for every 10 MPa increase in sandwich concrete strength. The initial stiffness of members increases with the rising compressive strength of sandwich concrete, but its downward trend becomes steeper, and the ductility of the member becomes worse.

![Figure 6. Load-displacement curve under the influence of sandwich concrete strength.](image)

5.4. Deformed Bars

Figure 7 demonstrates the load-displacement curve under the influence of deformed bars. When the wall thickness of the steel tube is 5 mm, 6 mm and 8 mm, the ultimate bearing capacity of the deformed bar is increased by 5.9%, 5.7% and 5.8%, respectively. The ultimate bearing capacity of the composite member can be increased reinforced with deformed bars.
6. Conclusion
FEA was conducted to investigate the axial compression performance of RHCFSSST short columns, and the conclusions can be summarized as follows:

(1) The whole loading process of the member can be mainly split into four stages: elastic stage, elastoplastic stage, descending stage, and gentle stage.

(2) For RHCFSSST, increasing the steel ratio, steel yield strength, sandwich concrete strength, and reinforced with deformed bars can increase the ultimate bearing capacity of the members. The descending order of the positive influence of each parameter on the ultimate bearing capacity of members is shown as follows: sandwich concrete strength, steel ratio, steel yield strength, and reinforced with deformed bars.

(3) For RHCFSSST, increasing the steel ratio, steel yield strength and reinforced with deformed bars can improve the ductility of members, but rising the sandwich concrete strength will weaken the ductility of members. The influence of each parameter on improving the ductility of members from high to low is as follows: steel yield strength, steel ratio and reinforced with deformed bars.

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