

Finite Element Analysis of Axial Compression Performance of Stainless Steel -Steel Tube Sandwich Concrete Columns

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Abstract. A finite element analysis software, ABAQUS, was used to numerically analyze nine specimens with varying inner steel tube thickness and slenderness ratio to study the axial compression performance of stainless steel - steel tube sandwich concrete columns. The influence of each parameter on the axial compression behavior was explored. The simulation results aligned closely with the experimental results, with the ultimate bearing capacity prediction error within 5%. Bulging deformation consistently occurred on the upper outer steel tube. Increasing the inner steel tube thickness improved the ultimate bearing capacity up to 20%, with the 4-6 mm wall thickness range providing the most effective capacity increase. The ultimate bearing capacity deteriorated up to 5% as the slenderness ratio increased, but the axial compression stiffness markedly decreased due to overall instability. A relationship between the stability coefficient and slenderness ratio was proposed, and the calculation results showed excellent agreement.

Keywords: Stainless steel - steel tube; Sandwich concrete; axial compression performance; Finite element analysis; Stability coefficient.

1. Introduction

Stainless steel is widely used in construction due to its aesthetic surface and superior corrosion resistance. Stainless steel tube sandwich concrete columns, comprised of ordinary carbon steel inner tubes and stainless steel outer tubes, are one such steel-concrete composite structure. These columns have similar performance to traditional steel tube concrete but with additional advantages like lighter weight, higher stiffness, and improved fire resistance [1-2]. They hold great potential for buildings, bridges, and marine structures. Research on the axial compression performance of regular double-walled steel tube concrete columns is relatively mature, including experimental, finite element analysis, and analytical methods [3-5]. These studies demonstrate the critical influence of the inner tube diameter-to-thickness ratio and slenderness ratio on mechanical properties.

For stainless steel tube sandwich concrete columns specifically, axial compression tests on short columns by Tang et al. [6] showed excellent compressive performance with varying outer tube thicknesses and concrete strengths. However, parametric analysis is still lacking for this composite type, particularly regarding the effects of the inner steel tube diameter-to-thickness ratio and specimen slenderness ratio on axial compression behavior, which remains unexplored. Therefore, to further advance research and application of these composite columns, this study utilizes ABAQUS finite element software to analyze the parameters of different inner tube diameters and thicknesses, aiming to provide insights for research and engineering applications moving forward.

2. Experimental programme

Tang et al. [6] selected three specimens with different stainless steel tube thicknesses for axial compression testing. All specimens had a height (L) of 360 mm, an outer stainless steel square tube edge length (d) of 120 mm, and thicknesses (t_1) of 3 mm, 4 mm, and 5 mm. The inner circular steel tube diameter (R) was 57 mm with a thickness (t_2) of 3 mm. Fig.1 shows the specimen cross-section. Due to the absence of a distinct yield point in stainless steel, 0.2 times the peak stress was used to determine the nominal yield strength. The measured nominal yield strengths of the 3 mm, 4 mm, and

5 mm thick stainless steels were 363 MPa, 550 MPa, and 586 MPa, respectively. The inner steel tube yield strength was 430 MPa. The concrete compressive strength of the C40 cube was 50.6 MPa.

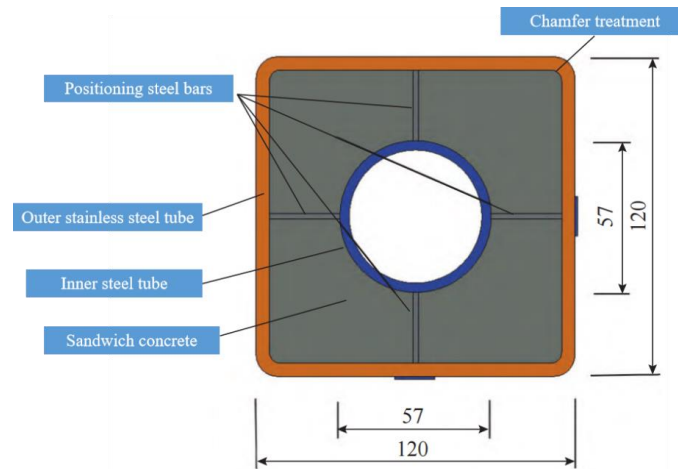
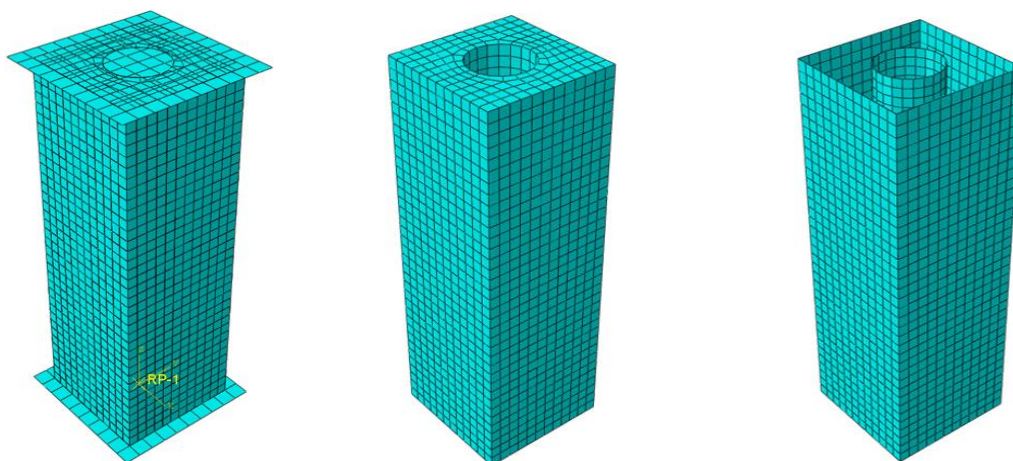


Figure 1. Schematic diagram of specimen structure.

3. Finite element model

3.1. Material properties and mesh size

The concrete was modeled using the concrete plastic damage model (CDP) with three-dimensional 8-node hexahedron C3D8R solid elements. The uniaxial concrete stress-strain relationship proposed in the Code for Design of Concrete Structures DB10010-2010 [7] was used for the constitutive model. For the stainless steel rebar, a constitutive model recommended by Wang et al. [8] was selected to account for the different behavior compared to carbon steel without a distinct yield plateau. A bilinear elastic-plastic model was used for the ordinary carbon steel, with elasticity prior to yielding and elastic-plastic behavior post-yielding [9]. A global element size of 20 mm was utilized to ensure high computational accuracy and efficiency. The completed finite element model is shown in Fig.2.



(a)The overall model. (b)Sandwich concrete. (c)Outer stainless steel and inner steel tube

Fig. 2 Modeling.

3.2. Interaction

A face-to-face contact was defined between the stainless steel tube, inner steel tube, and concrete using a hard normal contact and penalty tangential contact with a friction coefficient of 0.3 [10]. To improve convergence, steel plates were attached to the top and bottom specimen surfaces. A reference point (RP-1) was placed on the lower steel plate surface and coupled to the plate to apply axial loads and boundary conditions.

3.3. Boundary conditions and loading method

According to the experimental situation, constrain the displacement and rotation of the lower part of the specimen in three directions, simulate the fully fixed state of the lower part of the specimen, and apply a 20mm axial displacement consistent with the test at RP-1.

3.4. Validation of the numerical simulation model

The comparison of load-displacement curves ($P-\Delta$) between finite element simulation and testing is shown in Fig.3 (a). From Fig.3 (a), it can be seen that the load displacement obtained from finite element simulation is basically consistent with the test, and after reaching the peak load, it slowly descends into the gentle descent section, showing good ductility. The failure mode of the specimen is basically consistent with the experimental phenomenon [see Fig.3 (b)], and both exhibit the characteristic of bulging of the outer stainless steel tube. In addition, the ratio of the experimental ultimate bearing capacity to the finite element simulation value is 1.035, with an error of less than 5%, indicating that the established finite element model can better reflect the axial compression performance of stainless steel steel tube sandwich concrete columns.

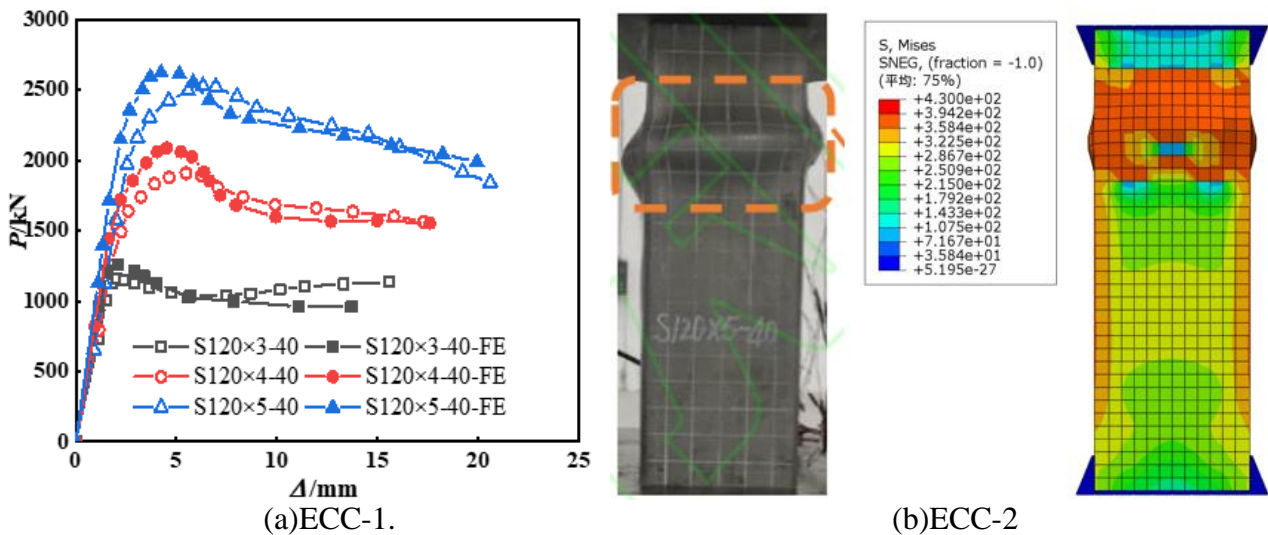


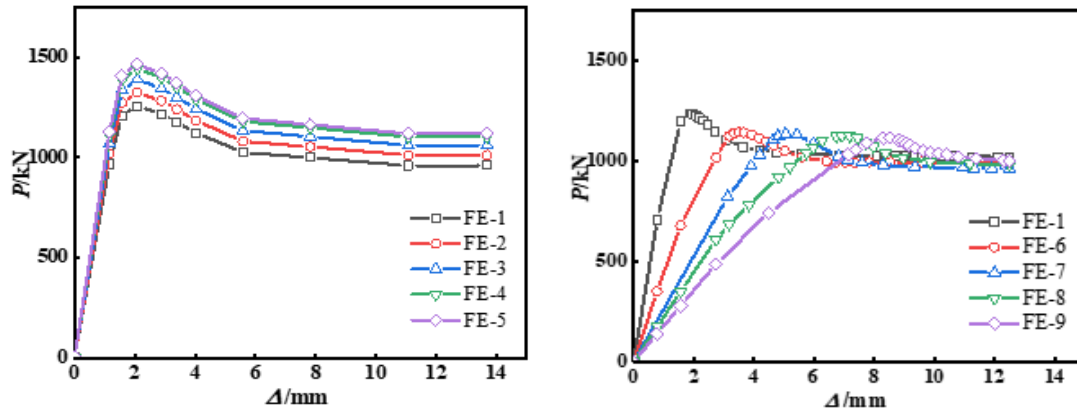
Fig. 3 Comparison between finite element results and experimental results.

4. Parameter analysis

Select specimens (S120x3-40) with a high degree of agreement between the load displacement curve and the failure mode as the reference model, establish 9 specimens, and discuss the effects of inner steel tube thickness t_2 and specimen height L on the seismic performance of stainless steel tube sandwich concrete columns. The parameters and results of each model are shown in Table 1, and the calculation method for slenderness ratio in the table is as follows $\lambda=L/d$.

4.1. Load-displacement curve

Fig.4 shows the comparison of load-displacement curves ($P-\Delta$) for each specimen. By comparing different variation parameters, the following conclusions can be drawn. As the thickness of the inner steel tube increases, the curve of the specimen increases in a parallel upward direction, indicating that the influence of steel tube thickness on the performance of stainless steel steel tube sandwich concrete columns mainly lies in the ultimate bearing capacity. As the slenderness ratio increases, the peak point of the specimen gradually moves downwards to the right, indicating a significant decrease in its initial slope, indicating a significant decrease in axial compression stiffness. This is due to the transformation of the specimen from local instability to overall instability, resulting in a decrease in axial compression stiffness.



(a)The influence of inner steel tube thickness. (b)The influence of inner steel tube thickness.

Fig.4 Load-displacement curve.

4.2. Axial compression bearing capacity and ductility

Table 1 shows the ultimate bearing capacity of all specimens, and the following conclusions can be obtained by comparing different variation parameters.

(1) As the thickness of the inner steel tube increases, the ultimate bearing capacity of the specimen gradually increases. Compared with the specimen with $t_2=3\text{mm}$, the ultimate bearing capacity of the specimens with t_2 of 4mm, 5mm, 6mm, and 7mm increases by 5.4%, 10.5%, 14.9%, and 16.5%, respectively. Overall, when t_2 increases from 3mm to 6mm, the ultimate bearing capacity increases by approximately 4.5% for every 1mm increase, while increasing from 6mm to 7mm only increases by 1.6%, indicating that increasing the steel content in the range of 3-6mm can more efficiently improve the bearing capacity.

As the slenderness ratio increases, the ultimate bearing capacity of the specimen gradually decreases. Compared with the specimen with $\lambda=3$, the ultimate bearing capacity of the specimens with λ of 6, 9, 12, and 15 decreases by 2.3%, 3.2%, 4.0%, and 4.8%, respectively. The slenderness ratio is a key influencing factor on the axial compression performance of stainless steel steel tube sandwich concrete columns. According to the model failure morphology, this is mainly due to an increase in the slenderness ratio of the specimen, leading to overall instability and reduced bearing capacity of the specimen. In the standard [7], for the method of calculating the bearing capacity of the normal section, the stability coefficient φ is directly related to the slenderness ratio λ . For the experimental value, φ is the ratio of the ultimate bearing capacity of specimens with different slenderness ratios to the ultimate bearing capacity of specimens with $\lambda=3$. Fit the relationship between the two using the least squares method [see equation (1)]. The comparison between the calculation results and the experimental results is shown in Fig.5, with a correlation coefficient of $R^2=0.98$, indicating a high degree of agreement.

$$\varphi = 0.00024\lambda^2 - 0.008\lambda + 1.02 \quad (1)$$

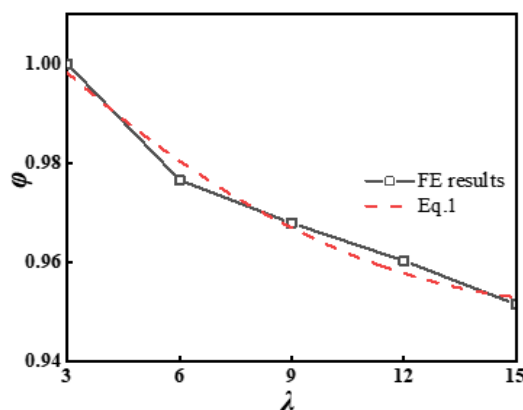


Fig. 5 Comparison of fitting results.

5. Conclusion

(1) The axial compression performance of stainless steel-steel tube sandwich concrete columns simulated using ABAQUS finite element software is in good agreement with experimental results, with an error in ultimate bearing capacity within 5%. The upper part of the outer steel tube shows consistent bulging deformation.

(2) Within the experimental range, as the thickness of the inner steel tube increases, the ultimate bearing capacity of the specimen increases within 20%. Considering the efficiency improvement, the wall thickness of the inner steel tube should be 4-6 mm.

(3) Within the experimental range, as the slenderness ratio increases, the ultimate bearing capacity of the specimen deteriorates to within 5%, but due to overall instability, the axial compression stiffness significantly decreases.

(4) The calculation relationship between stability coefficient and slenderness ratio was fitted using the least squares method, with a correlation coefficient of $R^2=0.98$, indicating excellent agreement.

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