Numerical Study on Oblique Hysteresis Performance of Composite-sectioned Square Concrete-filled Stainless Steel Tubular Columns

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Abstract. The composite-sectioned square concrete-filled stainless steel tubular column has the characteristics of high rigidity, strong integrity, reasonable force, beautiful structure and low maintenance cost. It has good performance in marine platform and cross-sea bridge structure and urban landmark buildings with high corrosion resistance. However, there are few studies on the performance and design methods of this kind of structure, which restricts its application. In this paper, Finite-element models (FEMs) for analyzing the tangential hysteresis behavior of the composite-sectioned square concrete-filled stainless steel tubular columns were established and verified. A parametric study was conducted on the influence of axial compression ratio, internal and external tube diameter ratio, and oblique angle. The calculated results showed that the composite-sectioned square concrete-filled stainless steel tubular column has good oblique hysteresis ability, but the larger axial pressure ratio or larger oblique angle will weaken the capacity, while the pipe diameter has little effect on it.

1. Introduction
With the rapid development of the economy and society today, the development trend of modern building structure can be summarized in three words: light, high strength and large span[1]. The composite-sectioned square concrete-filled stainless steel tubular column is a new type of combined column form. It has the following advantages: (1) high carrying capacity and good ductility. (2) High temperature resistance. (3) Wide range of applications [2]. The cooperative working mechanism between stainless steel tube and concrete of these new kinds of composite member is still unclear, especially the nonlinear cooperative working mechanism under earthquake. Solving this problem is the key to understand the working mechanism and mechanical essence of this new type of component. It is clear that the failure mode of the composite-sectioned square concrete-filled stainless steel tubular column and the influence law of important parameters are beneficial to reasonable section optimization in actual engineering design, improving the seismic performance of components and ensure seismic safety. This research can provide technical support for the formulation of seismic specifications and the promotion and application of such new composite structures. However, at present, domestic and foreign scholars have made many achievements in the research of stainless steel tube concrete members [3-5] and composite steel tube concrete columns [6,7] but the research on the oblique hysteretic behavior of the composite-sectioned square concrete-filled stainless steel tubular columns is rarely reported. This paper intends to study the oblique hysteretic behavior of this new type of components through
theoretical means, which is of great significance for the realization of scientific and reasonable component design and popularization.

2. Finite Element Model

2.1 Establishment of Geometric Models
The model is mainly composed of core concrete, laminated concrete, ordinary steel tube, outer stainless steel tube and other components. All components can be established by the extracting method in the part module. The specific operation method firstly defines the sections of each component on the sketch separately. Dimensions then stretched to the desired length of the part based on the section. The assembly of the model is carried out in the assembly module in ABAQUS, and the positioning of the components is completed by means of translation, rotation and the like.

2.2 Constitutive model of Material
Stainless steel stress-strain under load reciprocating relationship, provided ABAQUS mixed hardening model; the definition of "stabilized" characteristics may be employed. For the stress-strain relationship of ordinary steel under cyclic loading, this paper uses the double-fold line follow-up strengthening model. For the core concrete in the internal ordinary steel pipe, this section adopts the new three-stage model concrete under the constraints of the steel pipe to strain harden and soften the concrete: the interaction between steel tube and concrete is very small at the initial stage, at this time the concrete confined by steel tube. The stress-strain curve coincides with the unconstrained concrete stress-strain curve until after reaching the apex, the strain increases and the stress remains unchanged due to the constraint of the steel tube on the concrete. In the later stage, the concrete softens and the stress decreases. For the sandwich concrete and core concrete, the stress-strain relationship of the tensioned part adopts the unconstrained concrete tensile constitutive model proposed by Jumin Shen (1993). Finally, regarding the plastic damage of concrete, this paper adopts the concrete damage model of ABAQUS.

2.3 Contact Condition
When the stainless steel tube interacts with the concrete, "surface to surface contact" is adopted, and the stainless steel tube surface is set as the master surface, and the concrete surface is the slave surface, and the finite sliding mode is adopted. The contact relationship between stainless steel tube and concrete includes: in the normal direction, the normal contact between stainless steel tube and concrete is generally simulated by "hard contact"; the friction coefficient of common steel tube and concrete contact surface and for stainless steel tube and concrete are taken as 0.6 and 0.2 respectively, as the coefficients used in the literature [6]. The contact between the end plate and the stainless steel tube is "Shell-to-solid coupling". The clamp and the outer stainless steel tube are Tie-constrained.

2.4 Loading Method
Rotating a certain angle on the basis of the original coordinate system to obtain a new reference coordinate system, and setting a reference point at both ends of the member based on the new reference coordinate system and coupling with the end plate of the member, and setting the hinge at the reference point, and the shaft pressure \( N_0 \) is applied, and the shaft pressure \( N_0 \) is kept constant during the application of the reciprocating load. Due to the symmetry of the model components, it can be built into one-half model for simulation, and the symmetry plane is set to ZSYMM (\( U_3=U_{R1}=U_{R2}=0 \))at the mid-span interface. Since the angle of the oblique angle is set, the members are rotated at the required angle when the geometric model is established, and then the reciprocating load is applied to the composite-sectioned square concrete-filled stainless steel tubular column through the rigid fixture.
2.5 Meshing
The stainless steel tube adopts a four-node reduced integration format (S4R) shell unit, and uses 9 points of Simpson integral in the thickness direction of the shell unit. Laminated concrete, core concrete, fixtures and end plates are all three-dimensional solid elements (C3D8R) in an eight-node reduced integration format. The unit meshing is performed by a structured adaptive meshing method, which can obtain regular hexahedron or quadrilateral elements.

![Finite element model (1/2 model).](image)

2.6 Case Verification
According to the literature [6], the hysteretic behavior of the composite-sectioned square concrete-filled stainless steel tubular columns is limited, and a typical component mentioned in the article is verified. According to the hysteretic behavior of the composite-sectioned square concrete-filled stainless steel tubular column, a constant axial force is applied at both ends of the member, and a vertical reciprocating load is set at the fixture. According to the model constructed by the paper, the hysteresis curve and the skeleton line can be obtained.

![Comparison of hysteresis curve and skeleton line results.](image)

3. Analysis of the Mechanism of Oblique Hysteresis

3.1 Destructive Modal Analysis
The composite stainless steel tube concrete specimen was bent. The steel tube near the upper and lower edges of the clamp bucked outward and developed toward the ring. Due to the effect of the reciprocating load, the upper and lower parts of the outer stainless steel tube eventually appeared obvious. In order to understand the concrete inside and the inner tube of the steel tube, the test piece is cut by the view section manager. Under the action of reciprocating load, the laminated concrete is cracked on both sides of the clamp, and a plurality of penetrating cracks appear in the concrete. There are a few cracks in the
core concrete. For composite members, due to the filling of the sandwich concrete and the internal concrete, the ordinary steel tube is basically not buckling.

3.2 Load and Mid-span Displacement Hysteresis Curve

The hysteresis curve is a comprehensive reflection of the seismic performance of the structure. The fullness of the curve is closely related to the energy consumption of the component. It can be seen from the Figure 2: the test results can better reflect the mechanical properties of the composite-sectioned square concrete-filled stainless steel tubular column. In the pre-loading stage, due to the small degree of tension (pressure), the hysteresis curve basically circulates linearly, and the loading and unloading hysteresis curves are basically coincident, and the components are basically in the elastic stage. In the later stage, as the tension (pressure) becomes larger, the member enters the plastic phase, the stiffness of the member gradually decreases, and the rise tends to be gentle.

3.3 Load and Mid-displacement Hysteresis Curve Skeleton Line

It can be seen from the skeleton curve of the Figure 2 that the skeleton curve of the component is S-shaped, indicating that the component has undergone three stages in the reciprocating loading process: the initial component is still in the elastic phase, and the stiffness of the component at this stage There is no obvious change; as the load increases, the slope in the skeleton curve gradually decreases, indicating that the stiffness of the member gradually decreases, and the member enters the strengthening phase, at which time the member has yielded; as the load continues to increase, the skeleton curve decreases. The trend, the slope also continues to decrease, indicating that the bearing capacity of the component is decreasing and the stiffness is further degraded, at which point the component enters the failure phase.

4. Parameter Analysis

In this paper, seven composite stainless steel tube concrete members and one stainless steel tube concrete were designed as comparative test pieces, as shown in Table 1. The axial compression ratio, the oblique angle, and the ratio of the inner and outer diameters were studied as a single variable.

| No | Section type | Component label | $B_0\times t_0$ (mm×mm) | $D_i\times t_i$ (mm×mm) | $D_i/B_0$ | $\theta$ (°) | $n$ | $N_O$ (kN) |
|----|--------------|-----------------|-------------------------|-------------------------|----------|------------|-----|-------------|
| 1  |              | SCAS1-1         | 120×2                   | 50×2                    | 0.42     | 45         | 0.3 | 267.9       |
| 2  |              | SCAS1-2         | 120×2                   | 50×2                    | 0.42     | 45         | 0.6 | 535.8       |
| 3  |              | SCBS1-0         | 120×2                   | 80×2                    | 0.67     | 45         | 0.05| 46.27       |
| 4  |              | SCBS1-1         | 120×2                   | 80×2                    | 0.67     | 45         | 0.3 | 277.6       |
| 5  |              | SCBS1-2         | 120×2                   | 80×2                    | 0.67     | 45         | 0.6 | 555.3       |
| 6  |              | SCBS2-0         | 120×2                   | 80×2                    | 0.67     | 0          | 0.6 | 555.3       |
| 7  |              | SCBS2-1         | 120×2                   | 80×2                    | 0.67     | 30         | 0.6 | 555.3       |
| 8  |              | SS1-1           | 120×2                   | -                       | 0        | 45         | 0.3 | 239.9       |

4.1 Axial Pressure Ratio

It can be seen from Fig.3(a) that the larger the axial compression ratio is, the more obvious the second-order effect of the component is, and the component under the load is destroyed more quickly, and the ultimate bearing capacity of the component is greatly reduced. When the axial pressure is relatively small, the stiffness of the component increases with the increase of the axial compression ratio, mainly because the axial pressure is relatively small, the deformation of the component in the elastic phase is small, the second-order effect is not obvious, and the pressure can reduce the cracking area of the concrete. The stiffness is slightly increased; however, when the axial pressure is relatively large, the
load is large, the second-order effect is gradually obvious, and the stiffness of the elastic phase is reduced.

4.2 Oblique Angle
The skeleton curves of the two test pieces are compared as shown in Figure 3(b). It can be seen that as the angle of inclination increases, the faster the component enters the plastic phase, the faster the peak load is reached. With the increase of the oblique angle, the skeleton members with the oblique angle greater than 0° have obvious descending segments, and the members with oblique 45° deformation have the fastest degradation rate, indicating poor ductility.

4.3 Inner and Outer Diameter Ratio
Figure 3(c) shows the influence of the ratio of the inner and outer tube diameter to the \( P-\Delta \) skeleton line of the composite stainless steel tube concrete bending member. It can be seen that as the size ratio of the inner and outer tubes increases, the inner tube section size increases, and more The inner concrete is well constrained by the inner steel tube, so the lateral bearing capacity is increased, and the inner and outer tube sizes are 0.42, 0.67, and the components are substantially coincident with 0. Therefore, the inner and outer tube sizes have little influence on the shape of the component skeleton line.

5. Conclusion
(1) The hysteresis curves of the six components are relatively full, indicating that the composite-sectioned square concrete-filled stainless steel tubular column has good oblique hysteresis performance. (2) As the axial compression ratio increases, the smaller the area enclosed by the corresponding hysteresis loop, the weaker its energy dissipation capacity, indicating that its ability to withstand earthquakes is weakened, and its stiffness is increased in the case of increased axial compression ratio. The faster the degradation, the greater the deformation of the member under the impact of the earthquake during the earthquake resistance. (3) The larger the angle of inclination, the lower the ultimate bearing capacity of the member, the smaller the displacement corresponding to the ultimate bearing capacity, and the faster the rate of load degradation. (4) As the size ratio of the inner and outer tubes increases, the cross-sectional dimension of the inner tube increases, and the inner concrete is well constrained by the inner steel tube, so the lateral bearing capacity increases, but the growth is not large, so the inner and outer tube sizes are compared with the shape of the skeleton line of the member. The impact is small.

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