Study on axial compression behavior of rectangular concrete filled steel tubular columns with Perfobond Leister Ribs

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Abstract: The built-in open-hole type stiffened rectangular steel tube concrete refers to a new combined structure formed by forming an open-hole steel plate in the longitudinal direction of the inner wall of the steel pipe and then filling the concrete. The PBL stiffener has the double functions of longitudinal stiffener and shear connector. In order to study the influence of stiffeners on the ultimate bearing capacity of rectangular CFST columns, the finite element model was established by ABAQUS and the parameters of the stiffeners were analyzed, including the aperture of the stiffeners, the spacing of the stiffeners and the width-thickness ratio. The results show that the finite element model established in this paper is in good agreement with the existing test data. The bearing capacity of rectangular CFST columns increases first and then decreases with the increase of the opening aperture of stiffeners, increases with the increase of the opening spacing, and increases with the decrease of the width to thickness ratio of stiffeners. The conclusions of this paper can provide some suggestions for the design of PBL stiffened rectangular CFST columns in practical engineering.

1. Introduction

The inner wall of the steel pipe is welded with a long stiffening rib, and holes are cut along the length direction, and then filled with concrete to form a PBL stiffened steel pipe concrete structure. This kind of stiffening rib has the function of both stiffening rib and shear connectors, which can not only strengthen the bond between steel panel and concrete, but also improve the local buckling resistance of steel tube. Based on the above advantages, PBL reinforced steel tube concrete structure has been used more and more in the belly bar of truss bridge, the tower of cable-stayed bridge and the pier of continuous rigid frame bridge.

Huang Hong et al. [1] carried out 14 axial compression tests of concrete-filled square steel tubular columns with ribs, taking the width thickness ratio of square steel tube and the height thickness ratio of stiffener as the main parameters. The stress-strain relationship, the longitudinal stress distribution of core concrete and steel tube and their interaction are compared no rib, single rib and double rib square concrete filled steel tubular axial compression mechanical properties of short column. The results show that the stiffener not only increases the longitudinal stress of the core concrete, but also significantly reduces the tensile stress zone of the pipe wall and improves the stability of the pipe wall. Liu Yongjian et al. [2] conducted an experimental study on a group of concrete-filled steel tubular short columns with high steel content and formed by welding, and found that after longitudinal ribs are opened, the stability of the panels can be guaranteed, the interaction with concrete can be strengthened, and the deformation ability is enhanced. By analyzing the force transfer performance of PBL stiffener at the interface of steel concrete, the mechanical characteristics of PBL stiffened concrete filled square steel tube are analyzed.
Cheng Gao et al. [3] conducted tests on 4 groups of 23 PBL stiffened square concrete filled steel tubular short columns, studied the influence of parameters such as width to thickness ratio of steel tube, stiffening rib type and aperture on their mechanical properties, and gave a formula for calculating the minimum stiffening stiffness coefficient of PBL.

The above research mainly studies the mechanical properties of PBL stiffened steel tube concrete column through the experimental method, and does not give the specific influence of stiffening rib parameters on the concrete filled steel tube column.

In this paper, an axial compression finite element model of PBL reinforced rectangular concrete-filled steel tubular column was established. The influence of initial defects and welding residual stress was considered, and the influence of stiffening rib parameters on the bearing capacity of PBL reinforced steel tubular concrete column was studied.

2. Finite element study
The finite element model of PBL reinforced rectangular concrete-filled steel tubular column under axial compression was established by the universal finite element software ABAQUS. The model was compared with the existing test results to verify the accuracy of the model, and the parameters of the stiffeners of the PBL reinforced steel tubular concrete column were analyzed.

2.1 Establishment of finite element model
The explicit method in ABAQUS can overcome the numerical convergence problem caused by the large deformation and contact of the implicit method. The research of Thai et al. shows that the explicit method can accurately predict the quasi-static behavior when the loading rate is controlled. At the same time, it gives the specific method of display analysis in ABAQUS/ Explicit. Based on this method, the finite element simulation of axial compression process of PBL stiffened rectangular concrete-filled steel tubular column is carried out in this paper.

The finite element model of PBL stiffened rectangular concrete-filled steel tubular column is shown in Fig. 1. In this model, the steel plate and PBL stiffener are simulated by 4-node reduction integral shell element (S4R), and the concrete filled by 8-node reduction integral solid element (C3D8R). It is found that when the mesh size of steel panel is about 5% of the width of the specimen, the calculation efficiency can be improved effectively while the calculation accuracy is guaranteed. Use the Surface to Surface (Explicit) contact option for contact interactions between steel plate and concrete. A "hard" contact is specified in the normal direction, which allows the surface to separate during stretching and does not penetrate during compression; In the tangential direction, the friction coefficient between steel plate and concrete is 0.25. The steel plate and concrete surfaces at the end are coupled to the reference points 1 and 2 at the center of the end section by using the "Coupling" constraint to facilitate the setting of boundary conditions and the application of loads. The steel section and concrete section at the bottom of the column are constrained by fixed connection. The steel section at the top of the column is only allowed to have axial displacement, and the translational and rotational degrees of freedom in other directions are restricted. The load acts on the steel plate and concrete at the same time. Displacement loading is adopted at the reference point 1 on the top surface of the column, and the average loading speed is 1mm/s, about 5~10 times of the actual test loading speed, which can shorten the calculation time on the premise of ensuring the calculation accuracy.
The five-fold elastic-plastic constitutive model proposed by Liu Wei, which is adopted for the stress-strain curve of steel, as shown in Fig. 2.

The stress-strain curve of concrete adopts the constitutive relation of core concrete considering constraint effect proposed by Han [4], as shown in Fig. 3.

The Technical Specification for Concrete-filled Steel Tube Structure (CECS159:2004) [5] stipulates that the defect function of rectangular concrete-filled steel tube is as follows:

$$\omega = \frac{\omega_0}{4} \frac{2mnx}{B} \left( 1 - \cos \frac{2mnx}{B} \right) \left( 1 - \cos \frac{2mny}{L} \right)$$  \hspace{1cm} (1)

Where, $\omega_0$ is the maximum allowable deviation outside the plane of the plate, which is 0.01B according to the Technical Code for Cold-formed Thin-walled Steel Structures GB50018-2002 [6]. The initial defect shape of ribbed rectangular CFST members is shown in Fig. 4.
Predefined residual stresses are applied in the model. The residual stress model adopts the simplified residual stress distribution model of welded rectangular steel pipe section proposed by [7], as shown in Fig. 5.

2.2 model validation

The axial load-displacement curve and ultimate strength predicted by the finite element model in this paper were compared with the experimental results in the literature, and it was shown in Table 1 and Figure 6. As can be seen from Fig. 6, this model can accurately predict the load-axial displacement behavior of PBL stiffened rectangular concrete-filled steel tubular columns, and the average and standard deviation of the ratio of finite element results to test results are 0.96 and 0.08 respectively (Table 1). In conclusion, the finite element model established in this paper is reliable. It can be used to study the mechanical properties of PBL stiffened rectangular CFST columns.

| The data source | Specimen number | H  | B  | t  | bs | ts | d  | y  | F/T |
|-----------------|-----------------|----|----|----|----|----|----|----|-----|
| Literature 3    | SCB20-1         | 600| 200| 4  | 60 | 4  | -  | -  | 0.92 |
|                 | SCC20-1         | 600| 200| 4  | 60 | 4  | 30 | 50 | 0.98 |
|                 | SCB30-1         | 900| 300| 4  | 90 | 4  | -  | -  | 0.99 |
|                 | SCC30-1         | 900| 300| 4  | 90 | 4  | 30 | 100| 0.95 |

The average 0.96
The standard deviation 0.08

Note: F/T is the ratio of the finite element of the specimen to the axial compressive bearing capacity of the test.
3. Parameter analysis

3.1 Parameter design
In order to analyze the influence of opening aperture, opening spacing and stiffening rib width-thickness ratio on the mechanical properties of PBL stiffened rectangular CFST columns, three groups of specimens were designed using finite element method to study the change of bearing capacity. LSC–PSC5 changed the opening diameter (0–2/3b_s), PSC6–PSC10 changed the opening spacing (1.5d–2.2d), and PSC11–PSC15 changed the width to thickness ratio of stiffening rib (10–27).

Table 2 Finite element parameter design

| Specimen number | L  | B  | t  | b_s | t_s | d  | y  |
|-----------------|----|----|----|-----|-----|----|----|
| LSC             | 900| 300| 4  | 90  | 4   | -  | -  |
| PSC1            | 900| 300| 4  | 90  | 4   | 20 | 100|
| PSC2            | 900| 300| 4  | 90  | 4   | 30 | 100|
| PSC3            | 900| 300| 4  | 90  | 4   | 40 | 100|
| PSC4            | 900| 300| 4  | 90  | 4   | 50 | 100|
| PSC5            | 900| 300| 4  | 90  | 4   | 60 | 100|
| PSC6            | 900| 300| 4  | 90  | 4   | 45 | 70 |
| PSC7            | 900| 300| 4  | 90  | 4   | 45 | 80 |
| PSC8            | 900| 300| 4  | 90  | 4   | 45 | 90 |
| PSC9            | 900| 300| 4  | 90  | 4   | 45 | 100|
| PSC10           | 900| 300| 4  | 90  | 4   | 45 | 110|
| PSC11           | 900| 300| 4  | 80  | 3   | 40 | 80 |
| PSC12           | 900| 300| 4  | 80  | 4   | 40 | 80 |
| PSC13           | 900| 300| 4  | 80  | 5   | 40 | 80 |
| PSC14           | 900| 300| 4  | 80  | 6   | 40 | 80 |
| PSC15           | 900| 300| 4  | 80  | 8   | 40 | 80 |

Note: L- column height, B- column width, t - plate thickness, b_s - rib width, t_s - rib thickness, d - rib opening aperture, y- rib opening spacing.

3.2 Influence of hole diameter
The figure 7 shows that compared with concrete filled steel tubular column of stiffener is not opening, the opening of stiffener can largely improve the bearing capacity of concrete filled steel tube column, PBL stiffening the bearing capacity of steel tube concrete column first increases with the increase of hole diameter of stiffening rib, after opening aperture is about 1/3 of the stiffener width, the bearing capacity is the largest.
3.3 Influence of opening spacing

The figure 8 shows that PBL type stiffening the bearing capacity of rectangular concrete-filled steel tube column with the change of hole spacing is relatively small, the influence of the overall bearing capacity increases with the increase of hole spacing, hole when spacing greater than 2 times of hole diameter, bearing capacity increases slowly, suggested that the design, PBL hole spacing of stiffening rib 2 times of hole diameter.

3.4 Influence of stiffening rib width to thickness ratio

It can be seen from Fig. 9 that the bearing capacity of PBL reinforced rectangular concrete-filled steel tubular columns has a relatively large influence with the change of stiffener width-thickness ratio, and the bearing capacity increases with the increase of stiffener width-thickness ratio. When the minimum stiffness of the stiffeners is satisfied, the ratio of the stiffeners to the width of the stiffeners can be appropriately reduced to improve the bearing capacity of PBL stiffened rectangular CFST columns.

4. Conclusion

The bearing capacity of PBL reinforced rectangular concrete-filled steel tubular columns is less affected by the spacing of stiffeners, but is relatively affected by the aperture of stiffeners and the
width-thickness ratio of stiffeners. Some suggestions are given for the design of web members of truss bridges, pylons of cable-stayed bridges and piers of continuous rigid frame bridges. However, there is no specific analysis on the interface interaction between the opening stiffener and the concrete in this paper, which needs further research.

Reference

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