Research on static performance of T-shaped stiffener Reinforced Box Space joints under Spatial Loading

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Abstract: The problem of inner partition reinforced box column are the weld quality, time-consuming and laborious. In view of the problem, T-shaped stiffener externally reinforced box space beam-column joint are proposed in this paper. The finite element simulation was used to study the evolution of the initial stiffness of the T-shaped stiffener reinforced joints under spatial static loading, and the mechanism of the mutual force transfer between the T-shaped stiffener and the H-shaped beam and square column are revealed. The beam section height, the width of the T-shaped stiffener web, the height of the T-shaped stiffener flange are analyzed which are the T-shaped stiffener geometric parameters. The static performance of the reinforced box space joints are gained. The results show that the plastic hinge of the T-shaped stiffener reinforced the space joint is formed in the distance from the beam flange which is the point connecting with the end of the T-shaped stiffener. Such as the stress distribution is reasonable. The bearing capacity, plastic limit bending moment and initial stiffness of the box space joint can be effectively improved with increasing of the beam section height, stiffener web width and stiffener flange height. Therefore, the external T-shaped stiffener reinforced square steel column H-beam space joint has good static performance.

1. Introduction
The weld quality of the inner partition reinforced box column is not easy to guarantee, and the process is time-consuming and laborious [1-2]. In view of the problem, T-shaped stiffener externally reinforced box space beam-column joint is proposed. Singapore L C Ting [3-4] and others have analyzed the mechanical properties of different forms of externally reinforced box-column H-beam joints by finite element method. The research results show that T-shaped stiffener compared with other forms, joints have more reasonable stress distribution, which is the most effective reinforcement method. S L Lee (1993) [5] and others have proposed a simple design method for T-shaped stiffener reinforced box column H-beam joints. In recent years, Chinese scholars have also carried out relevant research on T-shaped stiffener reinforced box beam column joints. The seismic response often has multiple characteristics, the stress of joints in the frame is characterized by spatial stress. However, the mechanical properties of T-shaped stiffener joints and frame structures are mostly concentrated in the plane, and the spatial stress characteristics of joints and structures are rarely considered.

L Jin, L P Chen [6] have proposed a box-column space joint reinforced with T-shaped stiffeners. Mechanical properties of the box space joints meet the seismic requirements on account of the plastic hinge can be moved outward, as shown in Figure 1. However, when considering the two loading methods of plane loading and space loading, the failure modes of the joint is distinguishing. Therefore, the static performance of T-shaped stiffeners reinforced box-column space joints will be studied under spatial loading.

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2. Finite element model

2.1. Establishment of finite element model
The ABAQUS finite element analysis software is used to establish the numerical model. The beam-column member adopts a linear finite film strain reduction integral format of quadrilateral shell element (S4R), as shown in Figure 2. The steel materials are selected as Q345B, and the constitutive relationship data obtained from the space corner column joints for test [7], as shown in Table 1. The elastic modulus of the material is $E = 2.06 \times 10^5$ MPa, and the Poisson’s ratio is $\mu = 0.3$. The square steel columns with the axial compression ratio of 0.2 [8], are applied a constant vertical load of 60kN to the steel column, and hinged constraints at the top and bottom of the box column. The H-beams have adopts static vertical monotonic load [9-10], and the loading method is space loading as shown in Figure 3.

Table 1. Constitutive relationship.

| $\sigma$ (MPa) | $\varepsilon$  |
|---------------|----------------|
| 415           | 0              |
| 435.2         | 0.011          |
| 455           | 0.0195         |
| 475.9         | 0.0317         |
| 490           | 0.0478         |
| 510.7         | 0.0867         |
| 530           | 0.1261         |
| 556.2         | 0.1873         |

2.2. Connection design
The length of the H-beam in the T-shaped stiffener reinforced box space joints $L = 1100$mm, and the height of the box column $H = 1750$mm. The specific size is determined according to the position of the steel frame beam-column reverse bending point under the horizontal load. By selecting different parameters of H-beam section height, T-shaped stiffener flange height, T-shaped stiffener web width, joint design and parameter analysis. In this paper, 3 sets of T-shaped stiffener externally reinforced box space joints are designed, with a total of 10 joint specimens, all of which are center column joints. The specimen numbers and parameter value of each component are shown in Table 2. T-shaped stiffener reinforced box shaped space joint. In the following text, it is named ST.

Table 2. Working conditions.
### Specimen group and number

| Specimen group | Specimen number | Column Beam | T-shaped stiffener |
|----------------|-----------------|-------------|-------------------|
| 1              | ST1             | 250 8 250 h 150 6.5 9 14 150 50 50 | |
|                | ST2             | 300 h 6.5 9 14 150 50 50 | |
|                | ST3             | 350 h 6.5 9 14 150 50 50 | |
| 2              | ST4             | 250 8 300 h 150 6.5 9 14 150 50 25 50 | |
|                | ST5             | 300 h 6.5 9 14 150 50 50 | |
|                | ST6             | 350 h 6.5 9 14 150 50 50 | |
| 3              | ST7             | 250 8 300 h 150 6.5 9 14 200 50 50 | |
|                | ST8             | 300 h 6.5 9 14 200 50 50 | |
|                | ST9             | 350 h 6.5 9 14 200 50 50 | |
|                | ST10            | 300 h 6.5 9 14 200 50 50 | |

#### 3. Analysis of finite element results

**3.1. Effect of beam height**

The stress trends of ST1, ST2 and ST3 are the same, so ST1 is selected to analysis the stress development trend. Figure 4 (a) is the stress distribution of elastic stage of ST1 (P = 213.47kN), at the beginning of loading, the stress of ST1 first appears at the joint of T-shaped stiffener flange and beam flange, and the joint of T-shaped stiffener corner and column web. With the increase of the load, it expands to both sides of the beam flange and T-shaped stiffener web respectively, and the stress develops rapidly at the joint of T-shaped stiffener flange and beam flange. The beam flange first yields, and the stress transfers to the web, and finally runs through the whole beam section. With the further increase of the load, the whole section enters the yield stage, forming the yield hinge line throughout the whole section of the beam, as shown in Figure 4(b) (P = 255.06kN). Finally, under the action of load, the connection between T-shaped stiffener flange and beam flange is damaged, and the plastic hinge is moved out better, as shown in Figure 4 (c) (P = 249.42kN).

![Figure 4](image_url) **Figure 4.** Von Mises stress distribution of ST1.

Under the condition that the parameters of the joints are the same size, the beam section height is increased from 250mm to 350mm, the bending moment-rotation curve of joints ST1-ST3 is obtained, as shown in Figure 5. Compared with ST2 and ST1, the plastic limit bending moment of ST3 is increased by 19.87% and 48.3%, respectively, and the initial stiffness is increased by 21.91% and 53.48%, respectively. The relationship between the initial stiffness of ST1-ST3 and the plastic limit bending moment is shown in Figure 6. It can be seen from the Figure that the initial stiffness of the joint increases linearly with the plastic limit bending moment as the beam section height increases. The change of beam section height is an important parameter that affects the performance of the joint. Therefore, a reasonable beam section height should be selected.
3.2. The effect of the height of T-shaped stiffener flange

The ST2 (P = 305.06kN), ST4 (P = 202.64kN), ST5 (P = 223.72kN), ST6 (P = 305.06kN) joint failure morphology and stress distribution are shown in Figure 7. It can be seen from the Figure that when the height of the flange of the T-shaped stiffener is 0mm and 25mm, the maximum stress area is concentrated on the connection position of the web of the T-shaped stiffener and the column web. Plastic hinges cannot be moved out effectively. With the height of the T-shaped stiffener flange increased to 50mm and 75mm, the plastic hinge is formed at the connection of the T-shaped stiffener flange and the beam flange, and the stress distribution is reasonable. T-shaped stiffener flange height is an important factor affecting the mechanical properties.

Figure 7. Von Mises stress distribution of the second group.

Figure 8 is the bending moment-rotation curve of the ST4, ST5, ST2 and ST6, corresponding to the height of the T-shaped stiffener flanges of 0mm, 25mm, 50mm, and 75mm, respectively. Compared with ST5 and ST4, the plastic limit bending moment of ST2 is increased by 4.68% and 21.77%, respectively. The plastic limit bending moment of ST6 is not improved compared with ST2, but shows a downward trend. Compared with ST2 and ST5, the initial stiffness of ST6 has increased by 4.75%, 9.86% and 16.47%, respectively. Figure 9 is a comparison of initial stiffness and plastic limit bending moment, it can be seen that the flange height increases from 0mm to 50mm, which can greatly improve the plastic limit bending moment. The height of the T-shaped stiffener flange increased from 50mm to 75mm, and the plastic limit bending moment of the joints was basically unchanged. The height of the T-shaped stiffener flange increased from 50mm to 75mm, the initial stiffness of the joint showed an upward trend. The above analysis shows that the height of the T-shaped stiffener flange is an important parameter that affects the performance of the joint. Reasonable selection of the height of the T-shaped stiffener flange can effectively improve the initial stiffness and plastic limit bending moment of the joint.
3.3. The effect of T-shaped stiffener web width

The ST7 (P = 1327.57kN), ST2 (P = 305.06kN), ST8 (P = 281.82kN), ST9 (P = 359.70kN) and ST10 (P = 199.94kN) joint failure morphology and stress distribution shown in Figure 10. It can be seen from the Figure that due to the short length of the web of the ST7, the maximum stress area is concentrated on the connection position of the T-shaped stiffener flange and the beam flange, and the welding of the T-shaped stiffener web and the beam-column position. The failures of ST2, ST8 and ST9 all occurred at the connection position of the T-shaped stiffener flange and the beam flange, forming a plastic hinge line penetrating through the beam cross section to meet the requirement of plastic hinge outward movement. The failure of the ST10 joint occurred at the connection position between the T-shaped stiffener web and the column web at the lower flange of the beam. The T-shaped stiffener web warped, and the plastic hinge could not be effectively moved outward.

![Figure 10](image)

Figure 10. Von Mises stress distribution of the third group.

Figure 11 is the bending moment-rotation curve of the third group, the width of the T-shaped stiffener web is increased from 100mm to 300mm. It can be seen from Figure 11 that the width of the T-shaped stiffener web is an important factor affecting the performance of the joint. As the width of the T-shaped web increases, the plastic limit bending moment and initial stiffness of the joint increase, but the plastic limit corner decrease in turn. Because as the width of the web increases, the rigidity of the joint in the supporting frame gradually increases, resulting in a smaller turning angle of the joint. Compared with ST10, ST8, ST2 and ST7, the plastic limit bending moment of ST9 is improved by 3.85%, 8.54%, 18.20% and 29.75%, respectively. The initial stiffness of ST9 is increased by 2.08%, 9.83%, 24.02% and 43.18% relative to ST10, ST8, ST2 and ST7, respectively. Figure 12 shows the relationship between the initial stiffness of the third group and the plastic limit bending moment. It can be seen from the Figure that increasing the width of T-shaped stiffener web properly can improve the initial stiffness and plastic limit moment of the joint, but when the width of T-shaped stiffener web increases to a certain extent, the plastic limit bending moment and initial stiffness do not increase, but show a trend of decreasing. Therefore, a reasonable web width should be selected.
4. Conclusions
For the T-shaped stiffeners reinforced the box space joints, the mechanism and failure mode of the joint have been studied, and the following conclusions have been obtained.

- The final failure of the joint is due to the whole yield section of beam, and the plastic hinge is better achieved.
- With the increase of the beam section height within a reasonable range, the mechanical properties of the joint can be improved significantly.
- When the width of the T-shaped stiffener web changing from 1 to 1.25 times the width of the beam flange, the joint exhibit the good mechanical properties.
- It is recommended that the height of the flange of the T-shaped stiffener should be one-third of the width of the web of the T-shaped stiffener.

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