Study on the Static Performance of H-shaped Steel Beam to Square Tubular Column Semi-Rigid Connections Steel Frame

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Abstract. In order to study the overall mechanical behavior of the new H-shaped steel beam to square tubular column semi-rigid connections in steel frame, the static performance, failure characteristics and bearing mechanism of the steel frame are studied by the medium-span static load test of the full-size steel frame and finite element simulation. The results show: when the vertical concentrated force is applied to the beam span, the buckling occurs in the mid-upper flange of the beam spans, and the plastic hinge is formed at the position of the beam span, while the deformation of the joint and the column is small, so the safety factor of the frame column and the joint region is high. Due to the semi-rigidity of the joint, the force and deformation of the joint region are smaller than the span of the beam, and the rotation angle of the joint meets the requirements for normal use of the structure. Therefore, the carrying capacity mechanism of the steel frame is reasonable.

1. Introduction

In recent years, the H-shaped steel beam to square tubular column frame structure system has been widely used in the field of fabricated buildings due to its good seismic performance, bearing capacity and economic benefits. At present, in the H-beam beam to square tubular column frame system, the beam-column connections are mostly semi-rigid connections. The researches on these frames are mainly focused on the mechanical properties of the semi-rigid joints. Li Guoqiang et al. [1] studied the influence of different parameters on the failure mode of extended endplate connections between rectangular tubular columns and H-shaped beams with single direction bolts; Zhuang Peng [2], Wang Yan [3] studied the characteristics of H-shaped steel beam to square tubular column-joint with inner sleeve based on theoretical model and finite element method. The performance of steel joints has a crucial impact on the overall mechanical properties of the frame, but the study of the mechanical properties of the frame should not be limited to the study of joints. Some domestic and foreign scholars have analyzed the mechanical properties of the overall frame structure with semi-rigid joints. Li Guoqiang, Wang Jingfeng et al. [4] conducted a vertical monotonic loading test on a two-story-two-span flat-end plate semi-rigid joint steel frame. The results show that the semi-rigid joints have higher stiffness and strength, and the ultimate rotation angle also satisfies the design ductility requirements; Liu Xuechun [5] and Bai Lili [7] respectively studied that the effect of joint stiffness change on the mechanical properties of the frame can not be ignored. Viet-Hung Truong[8], Sánchez- Olivares[9], He Jianian [10] optimize the design of semi-rigid connection steel frame, put forward the method of structural calculation and design. Now, the research on semi-rigid connections between square steel tubular columns to H-shaped steel beams is relatively sufficient, but the...
mechanical properties of steel frames with semi-rigid connections are seldom studied, which can not reflect the influence of semi-rigidity of joints on the overall mechanical properties of steel frames. Therefore, the research on the mechanical properties of integral steel frames with square steel tubular columns to H-shaped steel beams needs to be carried out and perfected urgently.

Zhang Zhixiong [11], Zhu Huaquan [12] and Leng Le [13] proposed a new type of H-beam to square tubular column interior joint with splicing outer sleeve and also studies the static performance and seismic performance of the joints.

In the paper, in order to study the overall mechanical properties of a new type of steel frame with assembled joints, a full-scale static test and finite element analysis are carried out. The mechanical behavior of the new semi-rigid joint to the integral steel frame is analyzed.

2. Test overview

2.1. Specimen design and fabrication
The steel frame design refers to the "residential design code" of China (GB50096-2011), taking the cold-bending square steel tube frame column with a vertical distance of 2.8m and a central distance of 3.5m. The column section is 200mm ×200mm×10mm, the beam is a welded H-shaped steel beam with a section of 250mm×150mm×5mm×8mm, the thickness of grooved outer sleeve, cantilever grooved steel beam, angle steel and stiffening rib in the joint area is 10mm. The specimens are all made of Q235 steel, and E43 type welding rod is used for welding. The high-strength bolts are all 10.9 class M20. Transverse stiffeners are set on both sides of girder web at the point of concentrated load loading in the middle span of H-shaped steel beam. The detailed size of the specimen is shown in figure 1.

![Figure 1 Detail drawing of the specimen size.](image1)

2.2. Material test
In accordance with the provisions of "tensile tests for metallic materials -- part 1: methods of test at room temperature" (GB/T 228-2010), the test results are shown in table 1-1.

| Specimen name                             | Yield strength $f_y$(MPa) | Tensile strength $f_u$(MPa) | Strong bending ratio $(f_y/f_u)$ | Modulus of elasticity $E$ (x10^MPa) |
|-------------------------------------------|----------------------------|----------------------------|----------------------------------|-------------------------------------|
| Steel beam flange                         | 306.06                     | 448.91                     | 1.47                             | 2.01                                |
| Steel beam web                            | 279.83                     | 443.59                     | 1.59                             | 2.02                                |
| Square steel tube column                  | 315.22                     | 468.46                     | 1.49                             | 1.93                                |
| Outer sleeve, cantilever channel steel, etc| 277.32                     | 450.28                     | 1.62                             | 2.04                                |

2.3. Test scheme
The test steel frame is arranged horizontally, and the column bottom is rigidly connected with steel
blocks fixed on the ground. The upper and lower sides of the column are respectively fixed by pad blocks and compression beams to prevent the out plane displacement of frame. The test frame is loaded at the mid span of beam by a jack. A preload of 5% ultimate load is applied before the formal loading. The formal loading adopts load control and takes 5kN as loading series. The loading site is shown in figure 2.

2.4. Measurement scheme
The load applied by the jack is measured by load sensor, and the mid-span deflection of the beam is measured by placing a displacement meter on the middle and lower flange of the beam span. Strain gauges or strain gauges are arranged in the joints and key areas of beam and column for strain measurement (figure 3).

3. Analysis of test phenomena and results

3.1. Test phenomena
At the initial stage of loading, the whole frame had no obvious deformation. Until the mid-span load of the beam was loaded to 233 kN, the deflection deformation of the frame beam was already obvious (figure 4(a)). When the loading continues, the beam was still deforming as shown in figure 4(b). Local buckling appeared obviously at the upper flange on the left side of the middle span of the beam. The amplitude and speed of load increased slow down. When the mid-span load value was 235.5kN, the upper flange of the beam at the left side of the loading point was seriously deformed, and the frame showed slight lateral plane displacement, but the in-plane deformation was still the main one. The web of the beam bulged and the area where the column came into contact with the lower angle steel member showed slight depression. As the load continued to increase, unloading occurred, deformation of each component increased, and cantilever grooved steel beam was slightly separated from the lower flange of the beam. Finally, the beam lost stability due to excessive displacement out of plane (figure 4(c)). At the end of the test, the main failure phenomenon appeared on the beam, and there was no obvious phenomenon in the joint area and column.
3.2. Analysis of beam mid-span load-displacement and mid-span load

Figure 5 Load-displacement curve of beam at mid-span.

Figure 5 shows load-displacement relationship of beam mid-span. It can be seen from the figure that at the initial loading, the load has a linear relationship with the mid-span displacement. When the load increases to 150kN, the frame enters the elastoplastic stage. Compared with the initial stiffness, the frame stiffness becomes smaller. In the strengthening stage, when the maximum value reaches 235kN, the horizontal section appears. In this stage, the upper flange of the left end of the beam loading point is caused by local deformation and buckling. With the increase of beam deformation, the eccentricity of the loading point is too large, the beam moves too much on the outside of the plane, and the load becomes smaller. After the curve falls, the deformation increases as the load drops, and finally the whole frame cannot continue to bear the load due to the instability outside the beam plane.

3.3. Stress and strain analysis of joints and key areas of beam and column

3.3.1. Stress and strain analysis of outer sleeve

Figure 6 represents strain variation curve of outer sleeve flange. It can be seen that the stretching effect of the outer flange of the upper outer sleeve causes the inner flange close to the beam and the axis to be compressed, while the squeezing effect of the lower flange causes the inner flange to be stretched. Therefore, along the axis of the column, the measuring points 19 and 20 are under compression, while the measuring point 21 is under tension.

Because point 20 is close to the neutral axis of the beam section, its strain variation amplitude is smaller than that of point 19 and 21, which are far away from the neutral axis of the beam section. As a whole, the strain at the flange of the outer sleeve is small.

3.3.2. Strain analysis of H-beam

1. Strain analysis of beam mid-span region

Figure 7 shows the relationship between the strain of strain gauge No. 42-47 and the load in the middle span of H-shaped steel beam. The relationship between load and strain is consistent with the load-displacement relationship, that is, when the load is greater than 150kN and the frame enters the elastoplastic stage, the strain in the mid-span region of the beam exceeds the yield strain of its corresponding plate in the later stage of the test (The dotted line in the figure represents the yield strength of the flange of the beam). In addition, the strain changes at measuring points 44 and 45 on the flange of the tension side beam are close to and both are greater than those at measuring point 47 on the web of the tension side beam, because the greater the distance from the neutral axis, the greater the stress. However, the strain change rules of measuring points 42, 43 and 46 on the compression side are complex, because they are affected by the local buckling of the upper flange plate. According to the failure mode and load-strain relation, the area is a dangerous area for the whole frame.
2. Strain analysis of steel beam joint area

The steel beam joint area is also an important part of the frame, so it is necessary to analyze the strain of the joint. As can be seen from Figure 8, before the load is applied to 150kN, the girder flange strain in the node area increases slowly with a small amplitude. When the load is greater than 150kN, the strain variation amplitude increases, and the strain at measuring points 39 and 41 exceeds the yield strain (the dotted line in the figure represents the yield strength of the girder flange). This is because the length of cantilever groove steel beam is small and the constraint on the frame column is insufficient. With the increase of load, the column will be slightly deformed, leading to the change of the neutral axis position of the beam and the phenomenon of uneven tension and compression. In general, the strain at this point do not exceed the strain in the beam span, and the stress in the beam joint area is smaller than that in the middle of the beam span, so the bearing mechanism is more reasonable.

4. Finite element analysis

4.1. Establishment of model

The finite element model is established by ABAQUS using material properties obtained from the material properties test.

4.2. Comparison of test results and finite element results

4.2.1. Contrast of failure characteristics

Since the ultimate load of the test is 235kN, the state of test specimen and finite element model at 235kN are selected for comparison.

The deformation of the beam is v-shaped, which is consistent with the beam deformation under concentrated load in theory. Figure 9 (a) (b) shows that the upper flange of the beam is subjected to compressive buckling and the lower flange is subjected to tensile damage. Failure characteristics of test and the finite element model is different is that in the experiment, buckling occurred on the left side of the loading point of the upper flange, and out-of-plane bulging occurred on the web of the mid-span region of the beam. However, in the finite element model, buckling occurred on both sides of the loading point. This is because the finite element model constraints are idealized. Figure 9 (c) (d) shows the deformation and damage of local area of the joint. It is mainly the slight sag phenomenon in the contact area between the column and the outer sleeve and the lower angle. Since this phenomenon is very slight, the finite element deformation results are amplified 5 times for obvious observation. It can be seen from the figure that the deformation in the joint area of the steel frame is very small, and most areas are in the elastic stage.
4.2.2. Comparison of overall static performance

Figure 10 Load-displacement curve of beam mid-span.

Figure 10 shows the comparison of load-displacement between test and finite element numerical simulation. The mid-span load-displacement curve of the test and finite element are generally consistent, and they all go through elastic section, strengthening section and horizontal section. In the online elastic stage, the stiffness of the test curve is slightly smaller than that of the finite element simulation, which is due to the processing error, installation deviation and other factors of the specimen. In the middle and late stage of loading, the curve of the load-displacement relationship in the middle span of the beam in the test falls, while the curve in the finite element simulation increases slowly. This is because in the process of the test, complete out-of-plane constraints cannot be achieved, and lateral displacement occurs outside the plane, leading to unloading. However, the difference between the ultimate load in the test and the finite element simulation is very small, so the influence of the out-of-plane constraint on the maximum bearing capacity is not obvious.

5. Conclusion

In this paper, static test and finite element numerical simulation are used to study H-shaped steel beam to square tubular column semi-rigid connections steel frame. The conclusions of this paper can be summarized as follows:

1) Under concentrated load, the mid-span upper flange of the steel frame beam first reaches buckling, while the deformation of the joint and column is very small. At this time, the stress and deformation of the frame column and the joints are in a safe state. In the entire process of stress, the beam bears most of the adverse effects of the load. Due to the semi-rigidity of the joints, the load effect has a small impact on the joints. The bearing mechanism of the steel frame is reasonable. Under the static load, the actual load of the steel frame in the beam span has exceeded the actual load and has a large stiffness.

2) When the load is applied on the beam, the Mises stress in the compression zone of the column flange near the beam side is large, but the value and the distribution area beyond the yield strength are not large, and the strength and ductility of the column are still in the safe range. In addition, due to the large equivalent stress here, it causes slight depression, which cannot be ignored in practical engineering.

3) The failure characteristics of the steel frame are consistent between test results and finite
element numerical simulation results, indicating that the finite element model has certain reliability. The results of finite element analysis show that plastic hinge is formed in the plastic zone of beam mid-span when the frame is destroyed, while the plastic hinge in the joint domain is not fully developed, so the frame still has some energy dissipation capacity.

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