Study on Mechanical Properties of Weakened Steel Frame Joints at Beam Ends

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Abstract. In order to study the hysteretic properties of steel frame T-shaped weakened joints, 12 groups of steel frame weakened joints and 1 group of common joints are designed with the weakened form, the weakened diameter and the distance from the weakened center to the column end as the parameters. Based on simplified mechanical model and material constitutive relationship, the finite element model is established by ABAQUS software to analyze the hysteretic properties of the joint specimen. By comparing with the existing test results of the weakened joint, both have a good agreement, and the rationality of the finite element model is verified. The simulation analysis of the weakened joints of the beam webs is carried out in the further and the load-displacement hysteretic curves are extracted as well as skeleton curves and stress cloud diagram of the joints. The influence rules of the weakened form, weakened diameter and weakened distance from the center to the column end on the seismic performance of the joints are obtained, and the design suggestions for the weakened joints are put forward. These can lay a foundation for time-history analysis of the frame structure with this kind of joints.

1. Introduction

In recent years, the steel frame structure has been widely used in multi-storey industrial plants and civil buildings due to its flexible layout and the ability to arbitrarily divide rooms[1]. However, the traditional beam-column joints of the steel frame structure didn't show the expected ductility in the Northridge earthquake in the United States in 1994 and the Kobe earthquake in Japan in 1995[2,3], but brittle failure occurred due to the insufficient plastic deformation capacity of the joints. The key improving the performance of rigidly connected joints is to improve the toughness of the joints and make the joints more secure and reliable, that is, the joints are strengthened or the beam sections are weakened. The strengthened joints usually show good performance, but the strengthened joints will correspondingly increase the overall project cost, and the reliability will be reduced through a large number of welded joints.

A large number of scholars at home and abroad have realized the advantages of weakened joints in earthquake resistance and start extensive and in-depth research work. J. W. Park[4] conducted a series of experimental studies on the joints with holes in the beam webs, and the results showed the plastic corner of the beam end of most specimens was above 0.04rad, and no crack appeared at the welding seam of the upper and lower flange of the beam root, but the strength of the specimens deteriorated greatly. According to the seismic design principles of strong columns and weak beams of steel frames,
and the idea of effectively controlling the position of plastic hinges on the beams, X. L. Wang and Z. Z. Yin [5,6] adopted the form of joints weakened by openings in the beam webs to promote the formation of plastic hinges, and five sets of specimens under repeated load history were tested for failure. The relevant mechanical properties of the members were tested, and the hysteretic performance and ultimate bearing capacity of beam-column joints were discussed.

Although there are many studies on weakened joints, few design suggestions are proposed for practical engineering. Numerical analysis of hysteretic performance of T-shaped rigid joints for weakened form has not been reported. By using ABAQUS finite element software hysteresis performance analysis of 12 groups of weakened joints and 1 group of ordinary joints is carried out, and the influence of different parameters on the mechanical properties of cross-shaped joints is investigated, at last design recommendations which can be operable for actual projects are put forward. These can provide guidance for seismic performance test of weakened joints at beam web.

2. Specimen design and main parameters
In order to investigate the influence of weakened beam web on the mechanical properties of beam and column frame joints, a total of 13 groups of joint specimens are designed. The weakened forms are round and square, and the main changing parameters are the distance from the weakened center to the column end (D) and the weakened diameter / side length (d /B). The Schematic diagram of weakened joints is shown in figure 1. The main sizes and parameters of the specimens are shown in table 1.

![Schematic diagram of the weakened joints at beam ends](image)

(a) Round weakened form  (b) Square weakened form

Figure 1. Schematic diagram of the weakened joints at beam ends

| Specimens  | Column sizes (mm$^4$) | Beam sizes (mm$^4$) | $n_0$ | Weakened form | d /B (mm) | D (mm) |
|------------|-----------------------|---------------------|------|--------------|----------|-------|
| XRJD-C-1   | 400×300×10×16         | 300×200×8×12        | 0.4  | Round        | 165      | 195   |
| XRJD-C-2   | 400×300×10×16         | 300×200×8×12        | 0.4  | Round        | 165      | 225   |
| XRJD-C-3   | 400×300×10×16         | 300×200×8×12        | 0.4  | Round        | 165      | 255   |
| XRJD-C-4   | 400×300×10×16         | 300×200×8×12        | 0.4  | Round        | 195      | 255   |
| XRJD-C-5   | 400×300×10×16         | 300×200×8×12        | 0.4  | Round        | 195      | 285   |
| XRJD-C-6   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 195      | 315   |
| XRJD-S-1   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 165      | 195   |
| XRJD-S-2   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 165      | 225   |
| XRJD-S-3   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 165      | 255   |
| XRJD-S-4   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 195      | 255   |
| XRJD-S-5   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 195      | 285   |
| XRJD-S-6   | 400×300×10×16         | 300×200×8×12        | 0.4  | Square       | 195      | 315   |
| PTJD       | 400×300×10×16         | 300×200×8×12        | 0.4  | ---          | ---      | ---   |
3. ABAQUS finite element analysis and verification

3.1 Simplified mechanical model and constitutive model
Frame beams and columns intersect to form joints, which have complex stress. Take the upper and lower columns in half, and form hinge bearings at both ends. The lower end restricts the displacement in the horizontal X and vertical Y directions, and the upper end restricts the displacement in the horizontal X direction. The member can rotate and apply a constant axial force on the top of the column. One half of the frame beam is taken to form a free end, and a monotonic load and a repeated load are applied. The steel is made of Q345 steel, considering the large displacement of the hysteretic analysis of joints, the steel enters the strengthening stage after yielding, and the stress increases with the increase of strain. Therefore, the bilinear follow-up strengthening model is adopted in the steel constitutive model, and the slope of the strengthening stage is set as $0.05E_s$ ($E_s$ is the elastic modulus).

3.2 Finite element model
The finite element software ABAQUS is used for the nonlinear analysis of hysteretic joints. The H-shaped steel column, H-shaped steel beam and stiffener are built by C3D8R element, which is a three-dimensional solid element with 8-joint linear reduced integral scheme. Beam, column and stiffener parts are created in the assembly function module, and each parts are assembled in the way of binding. This kind of constraint allows two regions with different meshes to be bound, and there is no relative movement between the bound parts. Sweep meshing technology is used to mesh the corresponding parts of the established non-independent entities to obtain hexahedral elements that are relatively easy to converge. The finite element model of the joints composed of beams with different weakened forms after meshing is shown in figure 2.

![Finite element model of three kinds of joints](image)

3.3 Experiment verification of numerical analysis
The load-displacement curve of the test joint B2 can be obtained through literature[4], and it is converted into the bending moment-angle hysteresis curve as shown figure 3. The finite element model of B2 joint is established by ABAQUS finite element software and nonlinear analysis is carried out. The parameters and loading scheme of the specimen are the same as the test, and the load-displacement hysteretic curve of B2 specimen is extracted. The bending moment-angle hysteresis curve is obtained through transformation. As can be seen from figure 3, both have a good agreement, therefore the modeling method of finite element model is correct.
4. Performance analysis of joints subjected to monotonic load

4.1 Monotonic load-displacement curves
The comparison of the monotonic load-displacement curves of specimens under different parameters is shown in figure 4. We can see weakened beam has little effect on the bearing capacity of the joint.

4.2 Stress distribution
The Visualization module of ABAQUS finite element software is used to view the stress cloud diagram of specimen joints.
Figure 5. Stress clouds of different specimens at different loading stages

From the distribution of the stress cloud in figure 5, it is shown that the maximum stress of the unweakened joint appears near the joint domain under monotonic load, while the maximum stress of the weakened joint appears at the cross section of the hole, and the vicinity of the hole is first to yield. It shows that the weakened joints can achieve the purpose of transferring the maximum stress of the beam flange to the outside, so that the plastic hinge can be formed at the section of the hole after entering the plasticity.

5. Conclusions
(1) Based on the simplified mechanical model and material constitutive structure, the corresponding finite element model was established and the correctness of the model was verified.
(2) The weakened joint at the opening of the beam web has sufficient plastic deformation capacity. The joint can reduce the stress on the beam flange of the joint, so the plastic hinge can realize to move outward.
(3) Design suggestions are proposed for the weakened form, diameter and distance from the center to the end of the column. When the weakened form is round, the value of the hole diameter is $0.55h_b-0.65h_b$. The position of the hole is $0.75h_b-1.05h_b$ ($h_b$ is the height of the beam web) from the center line of the hole to the surface of the column flange. When the weakened form is square, the side length of the opening is recommended to be $0.55h_b-0.65h_b$, and the opening position is $0.75h_b-0.85h_b$ from the column flange surface to center line of the hole.
Acknowledgments
This paper was supported by Scientific Research Fund of Institute of Engineering Mechanics, China Earthquake Administration(Grant No. 2020D07), Opening fund for Key Laboratory of the Ministry of Education for Structural Disaster and Control of Harbin Institute of Technology(Grant No.HITCE201908) and Guidance Project of the PetroChina and Chemical Industry Federation Science and Technology (Grant No. 2017-11-5).

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