Experimental and numerical investigations on mechanical behaviour of spatial beam to side column connection with T-stub

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Abstract. The prediction of the behaviour of spatial beam to column joints relies on experimental and numerical tests that provide accurate information for the mechanical characterization of the joints. This study focused on the seismic behaviour of semi-rigid beam to side column space joints which connected with T-stubs. Beam to side column joints in the steel frame structures were considered as research objects to perform a spatial pseudo-static test on two joint models of a spatial subdivision, with end column as the load mode. The models of spatial beam to side column connection with T-stub implemented in the ABAQUS which takes into account the non-linear geometrical and material behaviour, non-linear contact and slip. Based on the experimental and numerical results, analyses were conducted on the deformation characteristics, plasticity status and failure modes of the joints, as well as the strengths, rotational stiffness, hysteretic characteristics, ductility coefficients, and energy dissipation properties of different joints. The results indicate that under the action of a spatial load, the relevant mechanical properties of the spatial semi-rigid joints were affected to varying degrees.

1. Introduction
The numerous failures of fully welded moment connections during the 1994 Northridge and 1995 Kobe earthquakes have come under questioning on this kind of beam to column connections is reasonable [1-2]. Post-earthquake assessments revealed that most of the cracks were developed at top and bottom beam flanges that were fractured before deformation of plastic hinges in the beams [3], and beam to column joints connected with bolts have good seismic performance in seismic damage investigation. It is indicated that beam to column joints connected with bolts are alternative connections in steel frame structures. However, in steel frame structures the H-section columns were used because this kind of section leads to a lack of lateral stiffness in the plane containing the minor-axis. The H-section steel columns are largely applied since the problem of weaker lateral stiffness has been solved. In the design of spatial steel frames, beam to column joints must be considered as semi-rigid which means that they have the capacity of bending and rotation. Minor-axis connections are often assumed to be pinned in usual design, in which the outer plane deformation of the web of the column. The application of component method could help evaluating the behaviour of semi-rigid joints, according to Eurocode3 [4]. The behaviour of minor-axis joint is different from the major-axis
joint which the section of column is H-shaped steel [5], but theoretical models and experimental tests are still lacking. Therefore, research on the seismic behaviour of the spatial joint under space stress is considerable significance for guiding the seismic design of a steel-frame structure system.

Take the spatial beam to side column connection with T-stub as research object, beam to side column joints with different stiffness of T-stub were carried out to study the influence of mechanical properties. Thus, two sets of tests on spatial semi-rigid joints are presented in this paper, each comprising two specimens with different joints, the first set with weak stiffness of T-stub, and the second with stronger stiffness of T-stub than the first set. Under the condition that static load applied on the column end, the studies compared the mechanical behaviours differences between minor-axis and major-axis.

2. Experimental programme

2.1. Test specimens

The experimental testing programme consisted of two full-scale specimens, as shown in Figure 1, the specimens were designed to represent exterior beam to column subassembly with WH300×300×10×15 column and NH350×175×7×11beam. For each specimen, every beam was connected to the column with two T-stubs, one at the top flange and one at the bottom flange of the beam, as shown in Figure 2. M22Grade 10.9 frictional type high-strength bolts, which were arranged in 2 rows with two bolts for each row, were used to connect these T-stubs to the beam and column. The applied pre-tightening force and torque for each bolt were 190kN and 900 N·m according to the Chinese Standard [6]. The nominal material property of the column, beam and T-stub is given in Table 1. The joint with less stiffness of the T-stub is defined as JT1(T270×200×8×12), conversely, the joint with larger stiffness of the T-stub is defined as JT2(T270×200×9×14).

Table 1. Mechanical properties of the joint specimens fabricated from steel

| Steel category                                      | Test items                  | $f_y$ (MPa) | $f_u$ (MPa) | $A$ (%) | $A$ (%) | $E$ (GPa) |
|-----------------------------------------------------|-----------------------------|-------------|-------------|---------|---------|-----------|
| Columns’ web and flange average value of            |                             | 271         | 457         | 36      | 31      | 209       |
| tensile strength                                    |                             |             |             |         |         |           |
| Beam s’ web and flange average value of            |                             | 270         | 460         | 28.5    | 28      | 209       |
| tensile strength                                    |                             |             |             |         |         |           |
| T stub1s’ web and flange average value of           |                             | 260         | 446         | 36.5    | 33      | 207       |
| tensile strength                                    |                             |             |             |         |         |           |
| T stub2s’ web and flange average value of           |                             | 266         | 456         | 34.5    | 31      | 210       |
| tensile strength                                    |                             |             |             |         |         |           |

Figure 1. Joint model of test specimen.

Figure 2. Details of the connection.
2.2. Test setup and test

The 3D schematic drawing and a photography of the test setup are shown in Figure 3(a). The test setup was designed to simulate the actual boundary conditions of a beam to column joint subassembly in a moment-resisting steel frame under lateral loading (e.g. seismic loading). The south-north direction was defined as major axis plane of the joint, while the east-west direction was defined as the minor axis plane of the joint. Two pairs of horizontal actuators were placed in the test in the major axis plane and the minor axis plane. The major axis and the minor axis plane were orthogonal, and each pair of actuators was connected with an L reaction wall, and a horizontal load was applied at both ends of the joint column. Two axes of symmetry on the column cross section were considered as the loading direction in the test. With reference to the standard loading system for evaluating the seismic behavior of steel structural components in US FEMA461[7], displacement control was adopted to realize the loading in alternating cycles of the major axis and minor axis. The horizontal load was defined as the yield load $\delta_0$, when the strain value on the T-stub connection was monitored and shown to have reached the yield strain of the material test. The load curve of the test is shown in Figure 3(c). The column was subjected to a constant axial load of 200kN (corresponding to the axial load ratio of about 0.1) applied by a hydraulic jack set at the top of it, and universal sliding hinge support was set at the base of the column to realize the sliding displacement caused by a two-way orthogonal load. Movable hinge supports were set at the beam-ends in the east (E), west (W), and north (N) directions.

![3D Model](image-url)

(a) 3D Model

![Test site photo](image-url)

(b) Test site photo

![Loading history](image-url)

(c) Loading history

Figure 3. Test setup and loading history.
3. Numerical modelling

The numerical model developed in ABAQUS consists of sub-assemblages of a column and three beams connected to each other by T-stubs and bolted to the column flange and are representative of spatial joints of a moment-resisting framed structures. The lengths of the beam and the column are established according to the experimental tests setup used in the validation of the FE models. A series of contact interactions were defined between the connector and the column/beam, and between the bolts and the connected members. Surface-to-surface contacts with finite sliding were employed for all the contacting pairs, where “Hard” contact was assumed for the normal contacting behavior and a friction coefficient of 0.4 was assumed for the tangential behavior, as recommended by the Chinese Standard [6]. Figure 4 shows the meshing established for spatial joint model and individual components.

![Meshed parts of the FE model](image)

(a) Mesh of connection  (b) Mesh of bolt  (c) Mesh of T-stub

Figure 4. Meshed parts of the FE model.

4. Discussions of test and finite element results

4.1. Yielding Behaviors and Failure Modes

Test and numerical analysis associated failure mode of the JT1 and JT2 are illustrated in Figure 5–Figure 6 for each joint. The failure mode of the JT1 is characterized by fracture at the junction of the T-stub’s web and the flange. It shows that the T-stub connector with less stiffness govern the bearing moment of the joint JT1. Fracture of the column’s web along the line between the web and the flange was found to be the governing failure mode for JT2. The above analysis shows that the stiffness of the T-stub connector has a great influence on the failure mode of the spatial joints.

![Fracture failures of JT1 joint](image)

Figure 5. Fracture failures of JT1 joint.

![Fracture failures of JT2 joint](image)

Figure 6. Fracture failures of JT2 joint.
4.2. Bending moment bearing capacity and initial rotational stiffness

Figure 7 shows the comparisons of JT1 and JT2 moment-rotation hysteretic curves between the test and FEM results. It can be observed that the FEM predictions are in good agreement with the corresponding test results, which proves that the proposed FE models can well reflect the cyclic performance of the specimens. Table 2 lists the bending moment bearing capacity of the test specimens, it can be seen from the table that the yield bending moment bearing capacity and ultimate bending moment bearing capacity of the major axial plane of the joints increase with the increasing of the stiffness of the T-stub. Conversely, the yield moment bearing capacity and ultimate bending moment capacity of the minor axis plane of the joints decreased as the stiffness increases of T-stub, mainly due to the increase of the flange of the T-stub in minor axial plane, which aggravates the extrusion of the web of the column.

Figure 7. Finite element model and comparison of hysteretic curves between test and FE results.
Table 2. Test results and FEA results.

| Joint No. | Direction | Loading Direction | Yield state $M_y$ (kN·m) | Ultimate state $M_u$ (kN·m) |
|-----------|-----------|-------------------|---------------------------|----------------------------|
|           |           |                   | Test| FEM | Test| FEM |
| JT112     | North     | Positive          | 53.19| 83.49 | 156.15| 182.74 |
|           |           | Negative          | -71.16| -82.36 | -161.19| -167.13 |
|           | West      | Positive          | 45.37| 41.01 | 120.82| 128.15 |
|           |           | Negative          | -38.42| -35.39 | -107.27| -135.25 |
|           | East      | Positive          | 36.45| 36.79 | 137.45| 146.4 |
|           |           | Negative          | -44.68| -42.22 | -105.91| -140.17 |
| JT114     | North     | Positive          | 100.94| 100.06 | 197.74| 209.41 |
|           |           | Negative          | -97.66| -102.77 | -224.84| -194.22 |
|           | West      | Positive          | 44.68| 41.94 | 73.52| 82.48 |
|           |           | Negative          | -37.79| -35.4 | -74.38| -92.24 |
|           | East      | Positive          | 36.78| 37.84 | 73.02| 83.18 |
|           |           | Negative          | -41.98| -45.66 | -75.28| -93.12 |

Rotational stiffness of the joint before the yield load corresponded to the moment-rotation tangent stiffness. After entering the plastic state, the bending moment and the rotation angle showed nonlinear properties. For the purpose of convenience, secant stiffness was commonly used to represent the rotational stiffness. Hence, the rotational stiffness of the joint was calculated as follows:

$$K_y = \frac{+M_y + |M_u|}{+\theta + |\theta|}$$  \hspace{1cm} (1)

In the case of the JT1 test, the major axial plane of joint yield by the T-stub, reaching initial rotational stiffness of 11218.58 kN·m/rad, and the initial rotational stiffness of minor axial plane is 6538.35 kN·m/rad. The same situation in JT2 test, the initial rotational stiffness of major and minor axial plane is 14848.71 kN·m/rad and 7748.87 kN·m/rad respectively. It can be seen from the above analysis that the initial rotational stiffness of spatial joints increased as the stiffness of the T-stub increasing.

4.3. Ductility

The ductility factor of the joint is defined by the ratio of the relative rotation angle between the beam and column, and calculated by equation (2).

$$\mu = \frac{\theta}{\theta_y}$$  \hspace{1cm} (2)

Table 3. Ductility factor of specimens.

| Joint No. | Major axis | Minor axis |
|-----------|------------|------------|
| JT1       | 5.71       | 8.74       |
| JT2       | 4.98       | 6.52       |

From the ductility ratio $\mu$ point of view, the ductility factor of all the test pieces exceeded 3.0, showing that the connection is more ductile. The ductility of the minor axis plane is greater than that of the major axis plane, mainly due to the deformation in minor axis plane governed by the column’ web.
4.4. Energy dissipation capacity

In the case of the energy dissipation capacity of the joint, the equivalent viscous damping coefficient \( h_e \) was typically used to evaluate the energy dissipation behavior of the structure under the action of a cyclic reciprocating load. The calculation method for this coefficient is shown in Figure 8, while calculation results are shown in Table 4. As observed from Table 4, the equivalent viscous damping coefficient of a joint is the average value in the positive and negative directions of the major and minor axes. The equivalent viscous damping coefficient of the joints is also increased with the increasing of the stiffness of the T-stub.

![Figure 8. The equivalent viscous damping coefficient calculation diagram.](image)

Table 4. Equivalent viscous damp coefficient.

| Joint No. | Major axis | Minor axis |
|----------|------------|------------|
|          | TEST  | FEA | TEST  | FEA  |
| JT1      | 0.284 | 0.293 | 0.192 | 0.214 |
| JT2      | 0.295 | 0.315 | 0.251 | 0.267 |

5. Conclusions

Based on the experimental and numerical investigations observations, the following conclusions could be made.

1. The plastic zone of the major axis plane of the joint is produced at the interface between the web and the flange of the T-stub. The plastic zone of the minor axis plane of the joint is produced at the junction of the web and the flange of the column.

2. When the thickness of the flange of the T-stub is less than 12mm, the T-stub is easy to break and cannot provide high bending moment bearing capacity.

3. The ductility factor of all the test pieces exceeded 3.0, so the ductility of this kind of connection is superior to that of traditional connection.

4. Both the major and minor axis planes of this joint have good hysteresis characteristics and energy dissipation capacity.

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