Research on Mechanical Performance of the Connection of Fabricated Primary and Secondary Steel Beam

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Abstract. Due to many advantages, prefabricated buildings are the trend of future development. In order to study the mechanical properties of the steel structure beam-beam connection node, referring to related materials, this paper designs a bolted connection node between main and secondary steel beams. By changing the key parameters such as the thickness of the supporting plate and the diameter of the bolt, the finite element software ABAQUS is used to simulate the primary and secondary beam nodes. Based on the finite element results, the force mechanism, failure mode, flexural bearing capacity and rotational stiffness of the nodes are analyzed, and some parameter design suggestions are proposed: the thickness of the supporting plate should not be less than 8mm, and the bolt diameter should not be less than 20mm.

1. Introduction
Hawxwell and Tsavdaridis [1] in order to determine the performance and classification of the eccentric end plate connection of the primary and secondary beams, and compare it with the performance of the commonly used wing plate connection and partial depth end plate connection, the results show that: eccentric end plate beam-beam connection The stiffness and strength of the eccentric end plate connection are higher than the other two connections, and the eccentric end plate connection is classified as a semi-rigid connection. Katula and Dunai [2] studied the bearing capacity of the bolted end plate beam-beam connection node and the bolt force distribution and end plate deformation. Based on the evaluated test results, the failure mode was determined and classified, and the design was based on European norms (EC3) The method is compared and verified with the test results. Mohamadi-Shooreh et al. [3] proposed a three-parameter exponential model for empirical prediction of the relationship between the slab beam-beam node bending moment-rotation angle (M-θ) and the finite element software for 468 bolts. The plate beam-beam connection node is analyzed. It is concluded that the model has acceptable results, which is in good agreement with the actual connection behavior. Da Silva et al. [4] studied the influence of beam-beam structural connection (rigid, semi-rigid and flexible) on the non-linear dynamic characteristics of the rhythmic activities of the human body through finite element analysis. Wei Wenhui and Liu Suli et al. [5,6] conducted a test study on the bearing capacity of the high-strength bolted joints of the primary and secondary beams of steel structures, and discussed the yield load, ultimate bearing capacity and ultimate deformation capacity of the bolted joints of the primary and secondary beams. A more reasonable method of eccentricity value in the design and calculation of the bearing capacity of the connecting bolts of the primary and secondary beams is proposed. Mou Xiaoliang et al. [7] conducted a bending test on the
two primary and secondary beam bolted joints, considering the influence of the diameter of the connecting bolts on the performance of the joints, and analyzed the failure characteristics, flexural bearing capacity and stiffness of the joints; According to the EC3 standard, the bending stiffness of the connection node cannot reach the rigid connection, and can only be regarded as a hinged node in the calculation.

2. Node design

With reference to the Atlas of Steel Structure Node Connections for Multi- and High-Rise Buildings 03SG51 9-1 and "Steel Structure Connection Node Design Manual" and other materials, the BASE (ZC10) test piece was designed. By changing key parameters such as the thickness of the support plate and bolt diameter, two sets of test pieces were designed. The detailed parameter changes are shown in Table 1, and the detailed diagram of the test pieces is shown in Figure 1.

According to the "Steel Structure Connection Node Design Manual" [9], when the secondary beam and the main beam are connected by high-strength bolts (as shown in Figure 1), the torsion effect of the main beam is usually ignored in the connection calculation, and only the end of the secondary beam and the main beam are considered. The shear force between beams can be determined according to the following requirements.

(1) Under the action of the shear force at the end of the secondary beam, the force of a high-strength bolt is:

\[ N_v = \frac{V}{n} \] (1)

(2) Under the action of the eccentric bending moment \( M_e = V \cdot e \), the force of a high-strength bolt with the largest lateral force is:

\[ N_M = \frac{M_e \cdot y_{\text{max}}}{\sum y_i^2} \] (2)

(3) Under the combined action of the shear force and the eccentric bending moment, the force of a high-strength bolt with the largest lateral force is:

\[ N_{v,\text{max}} = \sqrt{N_v^2 + N_M^2} \leq N_{v,\text{bl}} \] (3)

\( N_{v,\text{bl}} \) is the shear capacity of a high-strength bolt.

(4) Thickness of support plate:

\[ t = \frac{f_w h_{wb}}{h} + 2 \sim 4 \text{mm} \] (4)

\( t_{wb} \) is the web thickness of the secondary beam, \( h_{wb} \) is the height of the secondary beam web, and \( h \) is the height of the supporting plate.

| Tab. 1 Parameters of the finite element models |
|-----------------------------------------------|
| **Grouping** | **Specimen number** | **Support plate thickness/mm** | **Bolt diameter/mm** | **Bolt preload/kN** |
| Group 1      | ZC6               | 10                             | 16                   | 100                |
|             | ZC8               | 6                              | 16                   | 100                |
|             | ZC10              | 8                              | 16                   | 100                |
|             | ZC12              | 12                             | 16                   | 100                |
|             | LS16              | 10                             | 16                   | 100                |
| Group 2      | LS20              | 10                             | 20                   | 155                |
|             | LS22              | 10                             | 22                   | 190                |
3. Finite element model

On the basis of considering material nonlinearity, geometric nonlinearity and state nonlinearity, this paper uses ABAQUS software to perform three-dimensional solid finite element numerical simulation analysis on the connection nodes of steel structure primary and secondary beams.

3.1 Material parameters

The main beam, secondary beam and connecting plate in this model are all made of Q345 steel, the material elastic modulus \( E = 2.10 \times 10^5 \text{N/mm}^2 \), Poisson's ratio \( \nu = 0.3 \). The stress-strain curve adopts a multi-line model that can give full play to the elasticity and plasticity of steel. The material properties of the supporting plate are the same as those of the primary and secondary steel beams. The material indicators of the steel and high-strength bolts are shown in Table 2. Shown.

| material type   | \( E/10^5\text{MPa} \) | \( \nu \) | \( \sigma_y/\text{MPa} \) | \( \sigma_u/\text{MPa} \) | \( \varepsilon_y/(10^{-2}) \) | \( \varepsilon_u/(10^{-2}) \) |
|----------------|------------------------|-----------|--------------------------|--------------------------|-----------------------------|-----------------------------|
| Beam steel     | 2.10                   | 0.3       | 345                      | 470                      | 0.05                        | 19.8                        |
| High-strength  | 2.00                   | 0.3       | 800                      | 1000                     | 0.15                        | 5.15                        | bolts

Note: \( E \) is the modulus of elasticity; \( \nu \) is the Poisson's ratio; \( \sigma_y \) is the yield strength; \( \sigma_u \) is the ultimate strength; \( \varepsilon_y \) is the yield strain; \( \varepsilon_u \) is the ultimate strain.

3.2 Solid modeling, contact, boundary conditions and loading system

In order to simplify the calculation, this paper ignores the influence of geometric initial defects and residual stresses of the components. The finite element model is established in ABAQUS. All components adopt 8-node hexahedral linear reduction integral unit C3D8R, and the core area of the node is meshed and encrypted. The finite element model is shown in Figure 2. The section size of the main beam is H350×175×7×11, and the beam length is 2400mm; the section size of the secondary beam is H250×125×6×9, and the beam length is 1200mm; it is connected by 10.9 high-strength bolts. The model adopts the general contact type, the normal direction is set to "hard" contact, the tangential direction is selected as the "penalty" function, and the friction coefficient is set to 0.4. Different diameter types of bolts are applied with different pre-tightening forces. See Table 1 for specific data. The X, Y, and Z direction linear displacement limits are imposed on both ends of the main beam, and only the two ends of the main beam are allowed to rotate around the X axis. In addition, lateral constraints are applied to the middle of the secondary beam to prevent the secondary beam from out-of-plane instability during the load loading process; a displacement load in the Y-axis direction is applied to the cantilever end section of the secondary beam, and the loading method is shown in Figure 2(a).
4. Analysis of numerical calculation results

4.1. Force and failure mechanism
In view of the similar force and failure mechanism of the two sets of specimen models, the internal force transmission path is that the shear force of the secondary beam web at the node connection is transmitted to the support plate through the high-strength bolts, and then the force of the support plate passes through the support plate and the welding seam of the main beam is transferred to the main beam, so only the BASE (ZC10) specimen is taken as an example to analyze its force mechanism in detail. For the connection of the secondary beam web, in the initial stage of loading, the shear force transmitted is less than the static friction between the plates, and no slippage occurs. When the interaction between the plates overcomes the friction between the plates, the bolts start to produce slippage. As the load increases, the slippage of the bolt continues to develop, and the bolt rod contacts the hole wall and squeezes each other. With the continuous deepening of the extrusion of the bolt rod and the hole wall, the plastic area near the bolt hole of the secondary beam web, especially the upper bolt hole, continues to expand, and the stress concentration is more obvious. As shown in Figure 3(bc), the bolt group has produced very obvious shear deformation, especially the upper and lower bolts, while the stress of the middle bolt is relatively small, and the shear deformation is not obvious; the final state of the specimen failure is secondary. The bolt holes on the upper part of the beam web and the surrounding area are locally buckled, and the upper and lower bolts produce obvious shear deformation and break.

For the main beam connection, as shown in Figure 3(d), the maximum stress area appears at the upper and lower bolt holes of the supporting plate and the stress concentration is very obvious. The stress around the bolt hole in the middle of the supporting plate is relatively small, because when the node area is under negative bending moment, the upper bolt hole is under tension, the lower bolt hole is under compression, and the middle bolt hole is under tension or pressure is very small, so it can be assumed that the neutral shaft is located at the middle bolt.

4.2. Analysis of model stress cloud diagram
The force modes and failure positions of the two groups of model specimens are basically the same. Taking into account the space, only the comparison of the stress cloud diagrams of the second group...
of model specimens (LS16, LS20, LS22) is listed here, as shown in Figure 4. Show. It can be seen from the graph analysis that (1) as the bolt diameter increases, the stress concentration on the bolt rod decreases, and the shear deformation of the bolt rod decreases. (2) For the surrounding bolt holes of the secondary beam web, as the bolt diameter increases, the maximum stress around the upper and lower bolt holes on the web increases and the maximum stress area spreads to the periphery. In addition, the deformation of the upper bolt holes also changes. In particular, the bolt holes in the upper part of the secondary beam of the LS22 specimen suffered obvious punching shear failure. (3) For the main beam supporting plate, as the diameter of the bolt increases, the maximum stress around the bolt hole increases, and the spread of the maximum stress area also increases, but the stress concentration around the middle bolt is Reduced.

The first group of test pieces are ZC6, ZC8, ZC10 and ZC12. Through observation and analysis of the simulation phenomenon of the test pieces, it can be found that when the thickness of the supporting plate is thinner, the maximum stress area around the supporting plate and the secondary beam web bolt hole is larger and the stress is concentrated. The greater the degree; the thinner the supporting plate, the more obvious the out-of-plane deformation and buckling of the supporting plate. When the thickness of the supporting plate is 6mm, the supporting plate will lose stability out of plane. This is because the smaller the thickness of the support plate, the smaller its strength and rigidity, which weakens the strength and stability of the connection node.
4.3. Analysis of bending moment-angle curve

In this paper, the bending moment-angle curve obtained by numerical simulation by changing the thickness of the support plate and the bolt diameter is shown in Figure 5. It can be seen from Fig. 5 that the changing trend of the bending moment curve of the two groups of specimens is roughly the same, which is divided into three stages: the linear elastic stage of friction transmission, the bolt slip stage and the elastic-plastic strengthening stage. At the beginning of loading, the three curves basically coincide and show obvious linear changes; as the load increases, the shear force of the bolt is greater than the friction between the plates and slippage occurs. The bending moment curve shows the increase of the nodal angle. The bending moment increases relatively slowly. With the in-depth development of bolt slippage, the bolt and the hole wall begin to contact and squeeze, and the bearing capacity of the joint increases; when the final bearing capacity increases to a certain extent, the bending moment angle curve tends to be horizontal, and the joint rotational stiffness begins to degenerate. However, the end of the curve of the ZC6 and LS22 models has a rising stage, which is due to the contact between the lower flange of the secondary beam and the support plate in the later stage and the compression phenomenon, which further strengthens the bearing capacity of the node.

4.3.1. The influence of support plate thickness.

As shown in Table 3, the sliding and bending moments of specimens ZC6, ZC8, BASE(10) and ZC12 are 11.88, 11.97, 11.94, 11.84kN·m, respectively. This set of data shows that changing the thickness of the support plate has almost no effect on bolt slippage. The ultimate bending moments of ZC6, ZC8, BASE(10), and ZC12 are respectively 15.56, 18.48, 17.86, 18.90kN·m, it can be concluded that the thinner the supporting plate, the smaller the ultimate bending moment, that is, the smaller the joint bearing capacity, but When the thickness of the supporting plate increases to a certain extent, the effect of the joint bearing capacity is not obvious; the ductility coefficients of the specimens ZC6, ZC8, BASE(10), and ZC12 are 4.75, 3.78, 4.13, 3.50, respectively, indicating that the supporting plate is thicker and the joint The ductility is reduced, but the support plate is too thin, and buckling failure occurs easily at the support plate. In order to ensure the strength and stability of the nodes and prevent premature buckling failure of the supporting plate, it is recommended that the thickness of the supporting plate should not be less than 8mm.

| Specimen | M<sub>a</sub> (kN·m) | θ<sub>a</sub> (rad) | M<sub>y</sub> (kN·m) | θ<sub>y</sub> (rad) | M<sub>u</sub> (kN·m) | θ<sub>u</sub> (rad) | μ |
|----------|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|---|
| BASE     | 11.94             | 0.03            | 13.00           | 0.04            | 17.86           | 0.165           | 4.13          |
| ZC6      | 11.88             | 0.03            | 13.06           | 0.04            | 15.56           | 0.193           | 4.75          |
| ZC8      | 11.97             | 0.03            | 13.23           | 0.045           | 18.48           | 0.173           | 3.78          |
| ZC12     | 11.84             | 0.03            | 13.22           | 0.05            | 18.90           | 0.175           | 3.50          |
4.3.2. The influence of bolt diameter. As shown in Table 4, the slip bending moments of the specimens BASE, LS20, and LS22 are 11.94, 19.43, and 22.32 kN·m respectively. This set of data shows that increasing the bolt diameter (at the same time increasing the bolt preload) can significantly improve Bolt slippage status; analysis of the yield bending moment and ultimate bending moment of the BASE, LS20, LS22 specimens shows that increasing the bolt diameter (at the same time the bolt pre-tightening force increases) can effectively improve the bearing capacity of the primary and secondary beam connection nodes; The ductility coefficients of the specimens BASE, LS20, and LS22 are 4.13, 2.50, 3.57, respectively, indicating that increasing the bolt diameter increases and the ductility of the specimen decreases. In view of the above results, it is recommended that the bolt diameter should not be less than 20mm.

4.4. Analysis of joint bearing capacity and stiffness

4.4.1. Analysis of joint bearing capacity. According to the finite element simulation phenomenon and failure mode of the primary and secondary beam connection nodes, under the action of bending moment, the force distribution of the bolt group of the primary and secondary beam connection nodes can be simplified as shown in Figure 6.

According to the force distribution of the bolt group as shown in Figure 6, the upper or lower bolts of the supporting plate receive the greatest force, and the bending bearing capacity is calculated as shown in equations (5) and (6):

\[
\begin{align*}
N_1 &= N_2 \\
M_b &= N_1 y_1 + N_2 y_2 \quad (5)
\end{align*}
\]

\[
N_{s, \text{max}} = N_1 = \frac{M_b}{y_1 + y_2} \leq N_v^{\text{pl}} \quad (6)
\]

According to the calculation formulas (5) and (6), the design bearing capacity (bending moment) of the bolted joints of the two sets of test pieces is calculated. According to the secondary beam section size and material data, the edge yield bending moment of the secondary beam can be calculated And the plastic bending moment of the full section, as shown in Table 5.

![Bolt force distribution diagram](image)

Reference [2] on the load-bearing capacity analysis and mechanical model of the steel-concrete primary and secondary beam connection composite structure, analyzes the internal force transmission path of the primary and secondary beam connection nodes in this paper, and the secondary beam web transmits the shear force Vp to the main beam through high-strength bolts The supporting plate, but
the shear force $V_p$ does not directly act on the center of gravity of the supporting plate. Due to the influence of the eccentricity $\Delta$, an additional bending moment $M_x = V_p \cdot \Delta$ is generated outside the plane of the supporting plate, as shown in Figure 7. The additional bending moment can be equivalent to two forces $F_p$, one force $F_p$ is directly transmitted to the upper flange of the main beam, and the other force $F_p$ directly acts on the supporting plate and the secondary beam web, so if the supporting plate is too thin, it is easy to cause The support plate buckles out of plane.

### Tab. 5 Flexural capacity of primary and secondary beam joints

| Bending moment          | Yield (①) | Limit (②) | Specification design (③) | Secondary beam edge (④) | Full section of secondary beam (⑤) |
|-------------------------|-----------|-----------|--------------------------|-------------------------|------------------------------------|
| BASE                    | 13.00     | 17.86     | 5.84                     | 106.74                  | 121.39                             | 0.73  | 0.45  | 0.12  | 0.17  |
| ZC6                     | 13.06     | 15.56     | 5.84                     | 106.74                  | 121.39                             | 0.84  | 0.45  | 0.12  | 0.15  |
| ZC8                     | 13.23     | 18.48     | 5.84                     | 106.74                  | 121.39                             | 0.72  | 0.44  | 0.12  | 0.17  |
| ZC12                    | 13.22     | 18.90     | 5.84                     | 106.74                  | 121.39                             | 0.70  | 0.44  | 0.12  | 0.18  |
| LS20                    | 19.43     | 25.25     | 9.11                     | 106.74                  | 121.39                             | 0.77  | 0.47  | 0.18  | 0.24  |
| LS22                    | 23.18     | 29.78     | 11.27                    | 106.74                  | 121.39                             | 0.78  | 0.49  | 0.22  | 0.28  |

![Fig. 7 Source of additional bending moments $M_x$](image_url)

4.4.2 Analysis of joint bending stiffness. Eurocode (EC3) [10] divides the joints into rigid, semi-rigid and hinged joints according to the initial rotational stiffness $S_{j,ini}$ of the frame beam-column connection joints. For unsupported structures, when the initial bending stiffness of the node $S_{j,ini} \geq 25EIb/Lb$, the node can be judged as a rigid node; when the initial stiffness of the node $S_{j,ini} < 0.5EIb/Lb$, the node is a hinged node; when $0.5EIb/Lb < S_{j,ini} < 25EIb/Lb$, it is semi-rigid connection, where $EIb/Lb$ is the stiffness coefficient of the secondary beam, $E$ is the elastic modulus of the steel, $I_b$ is the moment of inertia of the secondary beam section, and $L_b$ is the secondary beam span. For the classification of primary and secondary beam connection nodes in this article, you can refer to Eurocodes for the classification of beam-column connection nodes. Therefore for the BASE (ZC10) node: $25EIb/Lb = 1.69 \times 105kN \cdot m/rad$, $0.5EIb/Lb = 3.38 \times 103kN \cdot m/rad$, $S_{j,ini} = 5.04 \times 102kN \cdot m/rad$, $S_{j,ini}$ is less than $0.5EIb/Lb$, so according to European norms (EC3), the connection node of the primary and secondary beams is a hinged node.

5. Conclusion

This paper conducts finite element research on the mechanical properties of the two groups of primary and secondary beam connection nodes, and draws the following conclusions through analysis:

1. The final failure mode of the primary and secondary beam connection nodes is: significant shear failure occurs on the upper and lower bolts. It is recommended to increase the bolt diameter appropriately to improve the strength of the nodes.

2. The force process of the connection node is divided into three stages: the linear elastic stage of friction transmission, the bolt slip stage and the elastic-plastic strengthening stage.

3. The yield bending moment and ultimate bending moment of the primary and secondary beam joints are significantly smaller than the calculated value of the yield bending moment of the secondary beam edge; due to the influence of the eccentricity between the secondary beam web and the supporting plate, additional out of the plane of the supporting plate is generated. The bending moment reduces the stability of the joint.
(4) Increasing the bolt diameter can effectively increase the bearing capacity of the connecting nodes of the primary and secondary beams; increasing the thickness of the supporting plate will not improve the bearing capacity of the joints, but the supporting plate should not be too thin, because too thin is easy to buckle prematurely.

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