Experimental Research on Mechanical Performance of New Modular Steel Frame Joint

Peng Lin\textsuperscript{1, a}, Cong Jun\textsuperscript{2, b}, Zhang Lei\textsuperscript{3, c}, Chen Wenqiang\textsuperscript{4, d}

\textsuperscript{1}China State Construction Engineering Technical Center China Construction Industrial Engineering and Technology Research Academy Co., Ltd. Beijing, China
\textsuperscript{2}China State Construction Engineering Technical Center China Construction Industrial Engineering and Technology Research Academy Co., Ltd. Beijing, China
\textsuperscript{3}China State Construction Engineering Technical Center China Construction Industrial Engineering and Technology Research Academy Co., Ltd. Beijing, China
\textsuperscript{4}China State Construction Engineering Technical Center China Construction Industrial Engineering and Technology Research Academy Co., Ltd. Beijing, China

\textsuperscript{a}peng.l@csece.com
\textsuperscript{b}20459293@qq.com
\textsuperscript{c}744060118@qq.com
\textsuperscript{d}1552444867@qq.com

Abstract. Aiming at the problems of large interlayer displacement angle and low rotational stiffness of modular steel frame connection nodes, a new type of grouted interlayer joint was proposed, and the experimental study was carried out to observe the failure form and mechanical performance of the node. In order to study the stiffness and bearing capacity characteristics of the new grouting interlayer connection, 4 different joint specimens were tested and studied. The influence of the bolt connection at the node on the bearing capacity, rotation stiffness and ultimate rotation capacity of the grouting node is analyzed. The test results show that the bolt connection can ensure the integrity of the node and improve the stiffness of the node; Whether the column is filled with concrete has little effect on the mechanical properties of bolted joints, but has a more obvious effect on boltless joints, and the initial stiffness is increased by 20%.

1. Introduction
Modular steel structure has the advantages of fast construction and installation speed, recyclable recycling, etc., which meets the needs of green buildings and the development of building industrialization. With the advancement of the assembly process in the construction industry, modular steel structure buildings have received more and more attention. They are not only widely used in non-permanent buildings such as temporary deployment barracks and emergency disaster relief, but also in permanent construction projects such as hotels, apartments, and kindergartens.

In the modular steel structure, the beam-column connection nodes and the interlayer connection nodes have an important influence on the stiffness, strength and stability of the entire structure. Therefore, the node connection mode and connection performance have always been hot issues\cite{1,4}. Scholars have conducted a lot of research and proposed welding connection nodes, connecting plate...
connection bolt connection nodes, outer sleeve bolt connection nodes, cross plate bolt connection nodes, self-locking connection nodes, etc. In order to achieve the design purpose of strong columns and weak beams and strong nodes and weak members in modular steel structure, this paper designs a bolt connection based on grouting treatment, processed 4 node specimens, and performed unidirectional loading tests. The integrity of interlayer nodes, node stiffness and failure modes are researched. And compare them with finite element numerical simulation analysis and experiments to provide references for the design and use of subsequent grouting nodes.

2. Test Overview

2.1. Specimen design

This paper conducts an experimental study on the grouting interlayer node in the node area applied in a project. The beam-column connection specimens used in the test are taken from the typical element between the beam-column inverted points of a conventional multi-layer steel frame structure under lateral load. The test piece adopts a full-scale model, and a total of 4 test pieces are designed as shown in Table 1.

| Test Group | Specimen Number | Quantity | Connecting Bolts | Grouting height (mm) |
|------------|----------------|----------|------------------|----------------------|
| Group 1    | JD1            | 1        | M30              | 1500                 |
|            | JD1-F          | 1        |                  | 1500                 |
| Group 2    | JD2            | 1        | Not set          | 2400                 |
|            | JD2-F          | 1        |                  | 2400                 |

The node structure of the test piece is shown in Fig. 1. A tensile screw with a diameter of 28mm is installed in the column, the upper component column is 1435mm high, the beam length is 1850mm, the lower component column height is 285mm, and the grouting material is C40 concrete. The node structure of the first group is that the top and bottom corner pieces are set with M30 bolts for vertical connection, in which the grouting height in the JD1 column is consistent with the height of the steel bar at 1500mm, and the grouting in the JD1-F column is the same height as the column; There is no bolt connection between the upper and lower components of the second group. The grouting height in the JD2 column is the same as the tensile screw, and the grouting in the JD2-F column is the same height as the column. The beams and columns are all box-shaped sections, the section size of the column is 250mm×200mm×12mm, the section size of the bottom beam of the top frame is 350mm×200mm×10mm (height×width×the thickness of the web), and the size of the top beam of the bottom frame is 300mm×200mm×8mm. 10.9-grade friction type high-strength bolts are used. The other components and parts are made of Q235 steel, and the elastic modulus E=206GPa.
2.2. Test device and measuring point layout
A 50t hydraulic servo jack is used as the loading system to carry out the static loading test, as shown in Fig. 2.

![Test device and displacement measurement](image)

Fig.2 Test device and displacement measurement

The pressure sensor is used to measure the thrust load of the jack. The 4# is used to monitor the displacement at the loading control point, and the 1# displacement meter is used to measure the displacement of the bottom frame beam. The 2#-3# displacement meter is arranged on the same side of the column as the new displacement meter. They are located at the bottom of the bottom corner piece and the top of the top corner piece of the node domain, respectively, to measure the interlayer displacement and rotation deformation of the node domain. A lubricating pad is arranged between the ends of the top and bottom beams to ensure relative sliding. 14 strain gauges are pasted in the node area to measure the strain value of the node area, which is shown in Fig. 3.

![Strain gauge layout](image)

Fig.3 Strain gauge layout

2.3. Loading methods and destruction criteria
First carry out pre-loading, check the test equipment and equipment, and ensure that the test equipment, observation and acquisition instruments are in normal working condition. Then start the formal loading. The elastic stage adopts load control. The load of each level is about 5% of the calculated ultimate load; when the section of the specimen shows buckling deformation or the applied load reaches 80% of the ultimate load, the loading amplitude is reduced. After the load reaches the maximum value, it should continue to be loaded until the load drops to 85% of the ultimate load, then stop loading.

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

3. Loading Process and Destruction Mode
When the displacement angle of JD1 is loaded to 1/250, the upper assembly rotates slightly clockwise, when the displacement angle is loaded to close to 1/26, the upper and lower components and the connecting plate are slightly opened, the connecting bolts are not significantly deformed, and the
connecting welds of the column and the corner pieces are damaged, as shown in Fig. 4(a). The peak load observed during the loading process is 270.8kN, and the displacement of the loading point is 54.58mm at this time.

When the displacement angle of JD1-F is loaded from 1/250 to 1/50, the connecting plate and the upper and lower components are kept in close contact with each other. When the load is close to 1/30, the quilting of the upper assembly column and the corner piece is damaged, the opening gap at the connecting plate is slightly increased, and there is no obvious deformation of the beam member and the vertical connecting bolt, as shown in Fig. 4(b). The peak load observed during the loading process is 284.8kN, and the displacement of the loading point is 51.3mm at this time.

When the displacement angle of JD2 is loaded to 1/250, the column rotates slightly clockwise, and the connecting plate keeps close contact with the upper and lower components. When the displacement angle is loaded to close to 1/12, the concrete inside the column is squeezed and cracked, making noises. Cracks occurred in the welding seam at the middle connecting position of the top plate of the bottom corner piece, and the welding seams at the right-angle connecting positions on both sides of the column and the top of the corner piece cracked. The gap between the upper and lower components and the connecting plate was increased, and the beam members had no obvious deformation, as shown in Fig. 4(c). The peak load observed during the loading process is 385.7kN, and the displacement of the loading point at this time is 104.2mm.

When the displacement angle of JD2-F is loaded to 1/250, the test phenomenon is similar to that of JD2. When the displacement angle is loaded to close to 1/27, there is a misalignment between the corner pieces and the connecting plate in the horizontal direction, and there are obvious cracks in the connection weld between the top plate and the side plate of the bottom corner piece on the tension side, as shown in Fig.4(d). The peak load is 304.0kN, and the displacement of the loading point is 53.6mm at this time.

![Fig.4 Deformation diagram of specimen failure](image)

4. Test Results and Analysis

4.1. Test Results

The load-displacement curve and data of the test piece measured in this test are shown in Fig. 5 and Table2 (the displacement is measured by the new displacement meter), and it can be seen from the test results:

4.1.1. The failure forms of the specimens were similar, and they were all manifested as the weld failure at the middle connection position between the upper component column and the top of the corner piece.
During the entire loading process of the first group, the upper and lower components and the connecting plate always maintain a small opening gap, the integrity of the nodes is good, and the bolts are not significantly deformed or damaged. During the continued loading process of the second group, the welds at the right-angle connection positions on both sides of the column were also damaged, and the gap between the upper and lower components and the connecting plate was larger than that of the first group. Among them, there is a horizontal misalignment between the corner pieces of JD2-F and the connecting plate, And the welding seam of the corner fittings was damaged earlier;

4.1.2. There are differences in the bearing capacity, stiffness and ductility of each group of specimens. The initial stiffness of JD1-F in the first group of specimens is increased by 1.8% compared with JD1, and the ultimate bearing capacity is increased by 5%. Compared with JD2, the initial stiffness of the second group of JD2-F is increased by nearly 20%. However, due to the bolt-free connection, the integrity is poor during the loading process, rotation occurs, the weld is pulled apart earlier, and the ultimate bearing capacity is not improved.

4.1.3. Comparing different sets of specimens, the initial stiffness of JD1 is 13.38% higher than that of JD2. The initial stiffness of JD1-F is 12.78% higher than that of JD2-F. JD2 showed good ductility in the test specimens.

![Load-displacement curve](image)

**Fig.5** Test load-displacement curve

| Specimen Number | Initial Stiffness (kN·m·rad-1) | Yield load (kN) | Yield Bending Moment (kN·m) | Ultimate Load (kN) |
|-----------------|-------------------------------|-----------------|----------------------------|-------------------|
| JD1             | 10903.5                       | 259.6           | 363.4                      | 270.8             |
| JD1-F           | 11098.5                       | 270.9           | 379.3                      | 284.8             |
| JD2             | 9616.9                        | 344.5           | 482.3                      | 385.7             |
| JD2-F           | 11505.9                       | 283.9           | 297.5                      | 304.0             |

4.2. Comparison of finite element and test results

The universal finite element analysis software ABAQUS was used to simulate the test specimens. Using solid element modeling, the beams, columns and corners of the upper and lower components welded together are tied. The contact surface between the upper component, the connecting board and the lower component is set to contact. The nut is in contact with the upper and lower components, the screw and the hole wall. In the contact properties, the friction coefficient of tangential friction is set to 0.15, the normal friction is set to linear, and the contact stiffness is set to 0.2. The contact between the concrete poured into the test piece and the inner wall of the corner piece and the column, and the concrete and the inner screw are bound and restrained.
Compare the simulation value with the test results, as shown in Table 3. The results show that the two are in good agreement. The comparison between the failure mode of the finite element simulation and the test result is shown in Fig. 6-7, which are basically the same. Therefore, the finite element analysis method used in this paper can better simulate the characteristics of the ultimate bearing capacity and failure mode of grouting joints.

Table 3  Comparison Of Simulation And Test Results

| Type       | Specimen Number | Initial Stiffness (kN·m·rad⁻¹) | Yield load (kN) | Ultimate Load (kN) |
|------------|-----------------|---------------------------------|-----------------|--------------------|
| Test value | JD1             | 10903.5                         | 259.6           | 270.8              |
|            | JD1-F           | 11098.5                         | 270.9           | 284.8              |
|            | JD2             | 9616.9                          | 344.5           | 385.7              |
|            | JD2-F           | 11505.9                         | 283.9           | 304.0              |
| Simulation value | JD1             | 13825.0                         | 277.8           | 301.5              |
|            | JD1-F           | 14143.5                         | 277.4           | 296.5              |
|            | JD2             | 13625.5                         | 300.3           | 367.9              |
|            | JD2-F           | 13785.1                         | 273.1           | 295.7              |

Fig.6  Comparison of finite element and experimental failure modes

Fig.7  Load-displacement curve comparison chart
5. conclusion

Through the unidirectional loading test on the grouting node with or without bolt connection, and the comparative analysis with the finite element results, the following conclusions can be drawn.

5.1 In the grouting joint, the stress is relatively large

at the connection position between the bottom corner piece of the upper component and the column or the top plate, and the first damage occurs during the loading process, which leads to a decrease in the bearing capacity of the component. Therefore, it is necessary to strictly control the quality of the weld in the joint connection to ensure the performance of the joint.

5.2 The integrity of the bolted connection node is better than that of the non-bolted connection node.

The opening gap between the boltless connection plate and the corner piece is more obvious, and more serious misalignment has occurred.

5.3 The bolt connection can improve the force performance of the node and increase the stiffness of the node,

which can be showed from the load-displacement results obtained through experiments and finite element analysis.

5.4 In the test results, whether the column is filled with concrete has little effect on the mechanical properties of bolted joints,

and only increases the stiffness of the joints by about 2%, which has a more obvious impact on the mechanical properties of boltless joints. The initial stiffness of the filled concrete column is 20% higher than that of the unfilled concrete.

5.5 Whether or not to install bolts has little effect on the initial stiffness of the concrete-filled nodes in the column, but it has a certain effect on the initial stiffness of the unfilled concrete nodes.

The stiffness of the nodes with bolts increases by about 13%.

Acknowledgment

Supported by scientific research project of “Research on Standardization Technology of Detachable Building Based on Assembled Technology” (Grant No. CSCEC-2020-Z-13) of China State Construction Corporation.

References

[1] CN-GB. Standard for Design of Steel Structures. China Architecture & Building Press, Bei Jing, 2017.
[2] Lu Junfan, “Study on mechanical properties of a new prefabricated steel structure node” Xi’ An University of Architecture and Technology, 2016.
[3] Lu Junfan, Hao Jiping, Xue Qiang, and Sun Xiaoling, “Study on mechanical performances of a new prefabricated steel structure node,” Building Structure., vol. 47(010), pp39-45, May 2017.
[4] Sun Fengbin, Liu Xiuli, Lu Yang. “Research progress of prefabricated steel structure beam column joint,” Steel Construction, vol. 34, no. 251, 2019.
[5] Wang Wenjing, Li Zhiwu, Yu Chunyi, Liu Yang, Ye Haowen, Li Zhenbao. “State of the Art of Modular Steel Building System,” Construction Technology, vol. 49, pp 24-30, Jun 2020.
[6] Guo Bing, Wang Lei, Wang Ying, Shi Yan, Tian Hailan. “Experimental study on rotational stiffness of steel frame beam-column connections,” Journal of Building Structures, vol. 32, no. 10, Oct 2011.