Research and prospect on column-column connection of assembled multi-layer steel structure

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Abstract: Assembled steel structure residential houses have the significant advantages of light weight, high strength and a high degree of utilization of space, which is an important development direction of the future residential industry for meeting the strategic needs of China's “four sections – environmental protection”, sustainable development of the construction industry, and the technical requirements of industrialization of housing construction. This paper reviews and summarizes the current status and research progress on the static performance and seismic performance of fabricated multi-story steel column-column connections, including connection types, tests, finite element analysis, etc. These results provide a reference for the further research work and establishing the design methods on column-column connections in the steel structures, as is expected to promote the application of the column-column connections in China's steel structure engineering.

1. Introduction
Due to its high strength, light weight, good plasticity and toughness, and short construction period, steel structures are widely used in various industrial and civil buildings, large-span structures, high-rise buildings and rail transit \cite{1}. The steel structure can be industrialized, and the bolt connection is used on site to facilitate full assembly and disassembly, shorten the construction period, and is suitable for building fully assembled buildings \cite{2-4}. The prefabricated steel structure overcomes the shortcomings of the traditional building structure, and gives full play to the advantages of “light, fast, good and economical” of the steel structure, by the key node connection, the prefabricated beams, columns and supports. All components are on-site splicing; Quality assurance is the reliability and integrity of the connection nodes, it is the most important and most difficult node to handle column-column connection. At present, many researchers at home and abroad have studied the column-column joints of fabricated concrete frame structures, and have obtained a series of research results \cite{5-11}. For the column-column joints of steel structure, there are relatively few connections.

2. Research of column-column joints for steel structure at home and abroad
For the assembled multi-rise steel structure, the typical domestic steel structure case is a Yuanda assembled steel structure (Figure 1), Hangxiao Steel Structure (Figure 2), China Construction Eighth Bureau (Figure 3), and Tsinghua University and Beijing Standard (Figure 4). Domestic and foreign scholars have explored and studied the connection performance and integrity of each component in
assembled steel structure. It mainly studies the hysteretic behavior of steel components such as welded box columns, cold-formed rectangular steel tube columns and round steel tube columns. But there are few researches on the connection of column-column joints.

At present, the column-column connection method of steel structure includes flange connection and high-strength bolts, and other strong welding [12]. Due to the high strength of the equal-strength welded joints and high safety performance, it is more common for the connection of the steel structure column-column joints in the initial stage. However, the survey found that about 150 high-rise steel structures in the Northridge earthquake in the United States were severely damaged. In the Japanese Hanshin earthquake, there were 476 steel structures collapsed and destroyed [13-15]. This is because the welded joint has the disadvantage of high initial residual stress and heat affected zone, so the flange bolt connection becomes one of the effective joint forms for welding.

Liu X C et al. summarized the results of research on the column-column connection of fabricated multi-story steel structures, and pointed out that domestic and foreign scholars have studied the performance of discontinuous and nonlinear changes in flange joint stiffness under tension [16-19], and established two A typical T-connector analogy and yield line theory [20-22], the research results laid a theoretical foundation for the further study of flange joints [2].

Zhang A L et al. used high-strength bolts to assemble the column seat and the column. The finite element numerical simulation and experimental study were carried out to analyze the force performance of the flange connection. The load-displacement curve and the bending moment-turn curve were drawn to verify the reliability of the flange connection [23].

By comparing rigid flanges and flexible flanges, Wang Y Q et al. studied the flexural load-bearing joints of square steel tubes and circular steel tubes. The results show that the ratio of the ultimate bending moment to the yield bending moment of the rigid flange joints is slightly. Less than the corresponding ratio of the flexible flange connection node, the force of the rigid flange connection node is smaller than that of the flexible flange connection node, and combined with the calculation model of the T-shaped end plate and the calculation theory of the yield line, the yield bearing capacity is proposed Simplified calculation formula [19, 24-25].

Gao W X designed four steel structural antique building square steel tubular columns and round steel tubular columns to connect the test pieces, focusing on the failure mode and seismic performance of the joint. The results show that the hysteresis curve is full, the stiffness degradation is small, the bearing capacity is high, and it has a good Seismic performance [26].

Figure 1 Yuanda assembled steel structure

(1) assembled steel structure
(2) Typical node connection
Liu X C et al. studied the mechanical behavior of multi-rise steel column-column joints under compression-bending-shear combination and bending-shear combination, and carried out full-scale model tests on four flanged columns with different flange thicknesses. The finite element analysis is used to analyze the influence of the axial pull ratio on the performance of the flanged joints. The sensitivity analysis of the parameters such as flange thickness and bolt edge distance under complex stress is carried out. Finally, the yield bearing capacity formula is proposed.

Wang Y et al. carried out a test study on the pre-tightening force of bolts on rigid flange joints and flexible flange joints. The comparison with the standard analysis found that the rigidity of the rigid flange and the flexible flange joint applying the bolt pre-tightening force (axial stiffness), shear stiffness and bending stiffness) are smaller than the normative value.

Luan et al. studied the mechanical properties of the flexible flange joints of the circular tube. The results show that the axial stiffness of the flexible flange joints is different when stretching and compressing.
Ding J et al. carried out a static and pseudo-static test on a full-scale model of a square-steel column with a steel plate tapping high-strength bolt under the action of compression-bending-shear combination. The test results show that the steel plate is used. The hysteretic curve of the flexible flange connection joint of the square steel pipe column with high-strength bolts is full and the ductility performance is good. The failure mode is the compression yield of the short steel pipe column [32].

Based on the above research results, it is found that the column-column connection is mostly flanged. The flange connection can be divided into flexible flange and rigid flange. The failure mode and seismic performance of the flange connection are mainly studied.

3. Experimental Research

The fabricated multi-layer steel column-column connection test includes a static test and a low cycle reciprocating horizontal load test. The static test mainly studies the failure mode and bearing capacity of the joints of the members. The low-cycle reciprocating horizontal load test is used to study the seismic behavior of the steel column-column joints. The seismic performance of steel-column-column joints is studied. The purpose is to study the hysteresis curve, skeleton curve, bearing capacity, ductility, energy consumption, strength and stiffness degradation of load-displacement, and the sensitivity of its parameters analysis [33].

3.1 Test conclusion

1) By full-scale model test and under the action of large bending moment and shearing force, Zhang A L [23] found that there was almost no displacement between the flanges, and there was no warping deformation. The connection was tight, so the column-column connection node of steel structure has good force performance; the flange connection node has the characteristics of quick installation and simple construction, and the site assembly does not require high technical content;

2) Gao W X studied the connection between the lower round steel pipe column and the upper square steel pipe column [26], because the bending stiffness of the circular steel pipe column section is much larger than the bending rigidity of the square steel pipe column section, the flange of the square steel pipe column and the web welding are found. There is stress concentration in the root of the seam, and the weld crack is prone to occur. Therefore, when the column end is loaded, the destruction of the entire component mainly occurs at the column end of the square steel pipe column;

3) Liu X C et al. found that the thickness of the flange plate significantly affects the stiffness of the flanged joint [27], and the flange angle increases as the flange ratio of the flanged joint column increases;

4) Wang Y et al. carried out a test study on the pre-tightening force of bolts on rigid flange joints and flexible flange joints [30]. Compared with the standard analysis, it was found that the rigid flanges and flexible flange joints with pre-tightening force of bolts were applied. The stiffness (axial stiffness, shear stiffness, and bending stiffness) are less than the specification values;

5) Luan studied the mechanical properties of the flexible flange joints of the pipe [31]. The results show that the axial stiffness of the flexible flange joints is different when stretching and compressing.

6) Ding J conducts static and pseudo-static test through the full-scale model of the joint of the steel pipe column flexible flange [32]. The test results show that the flexible flange connection node of the square steel pipe column with steel plate tapping high-strength bolt the hysteresis curve is relatively full and the ductility performance is good. The failure mode is the compression yield of the short steel pipe column.

4. Finite element analysis

The finite element analysis has the following three advantages: (1) it can accurately calculate the ultimate bearing capacity and rotation capacity of the joint, and clearly understand the detailed force of the joint; (2) can simulate the whole process of loading, observe the plastic development of the joint and obtain The bending moment-rotation angle of the connection; (3) A large number of parameter analysis can be performed to make up for the inadequacies of the test data, which can save the test cost.
For the related performance research of steel structure column connection, most of the current ANSYS and ABAQUS finite element software, ABAQUS is called "the most advanced large-scale general nonlinear finite element analysis software in the world".

4.1 Establishment of finite element model
(1) When numerical simulation by the finite element ANSYS, the steel pipe column selects the SOLID45 unit or selects the SOLID185 unit; the accuracy of the finite element analysis results depends largely on the treatment of the contact problem, and the column-column connection has the upper column and The contact between the inner wall of the lower column and the contact between the lower part of the upper column and the upper part of the lower column, etc., so the contact unit selects the 3D target element TARGE170 and the 3D8 node face element CONTA174;

(2) When using finite element ABAQUS for numerical simulation, the steel can adopt C3D8R unit, this unit is not affected by the analysis accuracy when dividing the grid; for the contact problem of steel structure column-column connection, hard contact can be adopted. The damping coefficient contact and the Coulomb friction model are used to solve the case where the calculation result does not converge.

4.2 The constitutive relationship of materials
Determining the constitutive relationship of steel materials is mainly a one-way axial pull test of steel. Shi Y J [34] and Wang Y Q [35] determined that the steel constitutive model adopts the hybrid strengthening model, which includes the characteristics of the isotropic model and the follow-up strengthening model. Shi Gang [36] found that the material constitutive relations of Q235, Q420, Q460 and Q500 steels were multi-linear isotropic strengthening models through experiments, seen Figure 5; When studying the Q550, Q620, Q690 and Q960 steels, it is found that the steel directly enters the strengthening stage after yielding. At this time, the constitutive relationship of the steel should adopt the trilinear isotropic strengthening model, seen Figure 6. Liu X C [27] uses a multi-linear isotropic reinforcement model with platform segments and a directly enhanced trilinear isotropic reinforcement model, seen Figure 7 and Figure 8; Gao W X [26] adopts the double-strength linear enhanced constitutive model, as shown in Figure 9. Zhang A L [23] uses a polygonal line-shaped constitutive model with a platform, as shown in Figure 10.

Figure 5 The constitutive relationship of steel [36]
Figure 6 The constitutive relationship of steel [36]
5. Conclusions and prospects

This paper reviews and introduces the research progress of multi-rise steel column-column connection at home and abroad on the material constitutive model, components, joints and experimental research. The results show that for multi-layer steel structure residential system, relative research of the connection of column-column nodes has been carried out less, mostly focusing on the research of beam-column nodes.

(1) The assembled steel structure residential house is light and high-strength, with high space utilization rate. It meets the strategic needs of China's 'four sections-environmental protection' and the sustainable development of the construction industry. It meets the technical requirements of housing construction industrialization and is the future residential industry development trend.

(2) At present, when studying the mechanical behavior of steel column-column connections, considering the nonlinearity of the material, the constitutive relation basically adopts a two-stage isotropic strengthening model or a three-segment linear isotropic strengthening model.

(3) Including the bending moment-rotation angle relationship and the hysteresis curve, the mechanical properties of the column-column connection node-flange connection can meet the requirements for steel structure.

(4) There are still many problems to be solved in the study of the column-column joints for multi-layer steel. For example, more tests are needed to verify, a new type of connection can be developed, and the column-column joints connected by applying pre-stress, et al.

Acknowledgments

The authors are thankful to the support of the Ph. D. funded project of Shandong Jianzhu University (00006015241) and the National Natural Science Foundation of China (51178258).

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