Research on the design and mechanical properties of new modular building joints

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Abstract. The key link of modular construction is to connect modules into a whole through the modular joints. Study shows that the modular structure from module between joints mostly happens to break, and modules joint will determine the bearing capacity of the whole building. Besides, the highlight and the meaning of the modular construction are to quickly build, and modular joint structure determines the construction speed. So modular joints play a very important part in the modular construction. At present, most of modular joints have some shortcomings. It is difficult to meet the construction installation requirements of modular building. So it has great significance to invent a joint which can achieve the fast construction aim, has reasonable construction method and has enough bearing capacity. A new type of modular joint is proposed in this paper, which meets all kinds of requirements of modular construction. The finite element analysis is used to analyze the stress nephogram and the moment-rotation curve to research its mechanical performance under five conditions. The results show that the new type of joint has a certain bearing capacity in each working condition.

1. Introduction
In recent years, the state has vigorously developed residential industrialization, promoted assembly-type construction, and built rapidly. The modular building is the result of the high development of prefabricated industrial buildings. It decomposes complex building structures and combines them into a building module at the construction site after prefabricating the modules. The prefabrication ratio of modular building is generally exceeding 85%, and the remaining small amount of work is to install and connect modular units at the construction site. It is the most advanced and thorough industrialization mode in the world.

Modular construction, which takes most of the work done at the factory, and a small number of construction methods completed at the construction site, with flexible design, low carbon energy, high efficiency manufacturing, rapid construction, high quality, economical, sustainable, safety and does not need the secondary decoration [1].

The existing inter-module joint structure mainly has the following types: The first type is the tie plate [2-3], and the adjacent modules are connected with the steel cover plate and bolts after the pre-punching construction site of the module corner is hoisted, as shown in Figure 1(a). The second type is the bolted end plate [4-5], and the steel plate welded at the column end is connected by bolts, as shown in Figure 1(b). The third type is the prestressed joint [6], and the elongated screw penetrates the entire column and then prestresses, as shown in Figure 1(c). The fourth type is the bolted connection with welded cover plate proposed by Tianjin University [7-8], which requires the opening at the beam column to provide the working surface, as shown in Figure 1(d). The fifth type is the bolted
connection with plug-in device [9-10]. The joint is designed with the inner sleeve and the tension bolts are used to connect the beams together, as shown in Figure 1(e). The sixth type is the bolted connection with rocket-shaped tenon [11], as shown in Figure 1(f).

![Schematic diagram of existing joints](image)

(a) Tie plate                          (b) Bolted end plate            (c) Prestressed joint
(d) Bolted connection with          (e) Bolted connection with         (f) Bolted connection with
    welded cover plate                       plug-in device                              rocket-shaped tenon

Figure 1. Schematic diagram of existing joints

2. Modular joint difficulties

Modular joints are the focus and difficulty of modular buildings. Joint performance will directly determine the overall performance of the building. There are four main difficulties in modular joints:

First, the central joint needs to connect 8 modules at the construction site as a whole;

Second, due to national policies, welding is prohibited on the construction site;

Third, due to the modular construction of the modular building after the module is assembled, it is difficult to find the construction working surface during assembly, especially the assembly of the last module, as is shown in figure 2;

Fourth, the original intention of modular building is to improve the efficiency of the building. Therefore, most of the modules are completed in the factory. When the module is assembling on site, it needs to avoid damage of decoration and avoid secondary decoration as much as possible.

![The last module is difficult to install](image)

Figure 2. The last module is difficult to install
3. New connection design and assembly method

In order to overcome the above difficulties and meet the requirements of modular building construction, a new type of beam-column without opening joints is proposed. The joints are as follows:

The connection structure schematic diagram is shown in Figure 2. The locating plate and the locating tube are sequentially welded into the square steel tube. The locating tube is the inscribed circle of the square steel tube, and the giant bolt is placed in the locating tube, and the prefabricated upper and bottom plates are welded at the end of column. This process is in the factory. The assembly diagram is shown in Figure 3(f). The assembly completed diagram is shown in Figure 3(g). In order to prevent the weld from cracking and improve the welding strength, the threaded end plate at the upper end of the column is divided into three parts for welding. The other processes of assembling the module at the factory are unaltered.

(a) Locating plate   (b) Locating tube          (c) Bolt            (d) Upper plate    (e) Bottom plate

The upper plate
Square steel tube column
Locating plate
Locating tube
Bolt
The bottom plate

(f) Assembly diagram           (g) Assembly completed diagram

Figure 3. The connection structure schematic diagram

Lift the fabricated module on the construction site, install the base plate after lifting the lower module (Figure 4), then lift the upper module, and then use the special twisting tool (Figure 5) to extend the giant bolt from the upper part of the column. The giant bolts connect the vertical modules together and connect the horizontal modules through the backing plate to achieve the effect of fixing the eight modules together. Figure 6 and Figure 7 are schematic diagrams of joints in 8 modules.

Figure 4. Base plate
Figure 5. Twisting tool
4. Abaqus finite element analysis of new connection

Five kinds of working conditions were selected for finite element simulation. The working condition is the upper end of the upper column. The working condition is to study the bending performance of the joint domain when subjected to vertical load. The working condition is the upper end of the upper column. The force is mainly to study the mechanical behavior of the nodal domain under horizontal loads such as wind loads. However, due to the above-mentioned working conditions, most of the loads are taken by the joints in the module, and it is impossible to thoroughly investigate the force performance of the connection between the modules. Therefore, three working conditions of column bending resistance, column tension and column shear are selected to investigate the connection performance between modules. The stress distribution of each working condition is mainly investigated. The weak point and failure mode are judged according to the stress concentration position. The bending moment curve of the working condition is also given to consider the performance of the joint. The bending moment curve is the main mechanical property of the joint. It reflects the initial stiffness, bending capacity and rotation ability of the joint, which directly affects the deformation, ultimate bearing capacity and overall performance of the building system.

Finite element analysis uses the mises yield condition. The elastic modulus of the steel is $E = 2 \times 10^5 \text{N/mm}^2$, Poisson's ratio $\nu = 0.3$. The steel is made of Q235 steel, and the bolts are of class 10.9. The small slip of the contact interaction takes a coefficient of friction of 0.4.

4.1. Working condition 1: Vertical loading of the beam end

The purpose of this working condition is to study the bending resistance of the joint subjected to vertical forces. The finite element model takes half of the joints for research, that is, four beams and four columns. The cross-shaped joint model is established at the inversion point of the beam and column according to the actual size of the module unit, wherein the column has a section of 150×150×8 and a length of 1.5 m. The beam size is 200×150×8, the ceiling beam size is 150×150×8, and the beam length is 3m. The boundary conditions are that the upper and lower beams of the beam end are respectively coupled with degrees of freedom and then hinged.

The loading method is to apply vertical displacement on the top of the column, and the total load is 240mm. As a result, the stress is mainly developed near the beam end joint area. The maximum stress except the bolt is near the joint between the floor beam and the angle steel, the bolt stress is the largest, and the bolt is laterally sheared. It can be seen that the bolt acts as a connection between the horizontal modules. Figure 8 is a vertical load stress diagram of the beam end.
Figure 8 Stress diagram of vertical loading of the beam end

Figure 9 is the moment-rotation curve of the joint between the column floor and top beam or the bottom beam.

4.2. Working condition 2: horizontal loading at the end of the column

The two ends of the beam are hinged, the horizontal displacement is applied after the upper end column is coupled, and the lower end column is coupled to the rear hinge. Figure 10 is a stress diagram after loading 120 mm.
4.3. Working condition three: column bending resistance

The two ends of the column are simply supported, and the two forces are loaded so that the joint is in a purely curved section to study the mechanical behavior of the joint under the bending moment of the column end. Figure 11 is a schematic diagram of loading. Figure 12 is a stress diagram after loading 80mm.

4.4. Working condition four: column tension

The column end is given a tensile force horizontal to the column to study the tensile properties of the joint. Figure 13 is a schematic view of loading, and Figure 14 is a stress diagram after the relative displacement of the two ends of the column is 100 mm. The visible force is concentrated in the middle of the column, and the final damage is that the large deformation of the right column is broken.
4.5. Working condition 5: Column is sheared
The backing plate is given a shear force perpendicular to the column to study the shear resistance of the joint. Figure 15 is a schematic view of loading, and Figure 16 is a stress diagram of loading 20 mm, which can be seen to be destroyed by large deformation of the pad.

5. Conclusion
In this paper, the difficulties of constructing the joints between modules are given. A connection joint between modules is developed for the difficulties. It can overcome all the difficulties mentioned, and its construction form and the assembly method are introduced in detail. The mechanical properties of the new type of joint under five working conditions were analyzed by ABAQUS finite element software. The working condition is that the beam of the column under pressure is bent, the stress is concentrated at the joint of the beam and the angle steel, and finally the beam buckling is broken.

Working condition 2 is that the upper end of the column is subjected to horizontal force, and the joint domain column is bent, and the stress is concentrated and deformed and destroyed. In the third case, the column is bent and the column is broken near the joint. The fourth working condition is that the column is pulled, and finally the middle part of the column is pulled. In the fifth case, the column is sheared, and finally the large deformation of the pad is destroyed. The new type of joint has a certain bearing capacity under all working conditions and has certain use value.

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