Design method and detailing requirements of a new type of fully assembled beam-column joints

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Abstract. With the innovation of steel structural joints, requirements for the reasonable design methods tend to be intensified to guarantee the effectiveness of joints’ working performance. To provide a certain reference for the design of assembled joints, related checking calculation methods and detailing requirements of a new type of fully assembled beam-column joints are given based on experimental phenomenon and according to related standards.

1. Introduction

Recently, the construction of prefabricated steel structures has been strongly promoted by the introduction of national policies and the requirement of building industrialization[1]. Because of the high material utilization, good mechanical performance, fast installation and light weight, steel structure is widely used and thoroughly studied as a green building system[2]. In the most construction of high-rise structure buildings, members are transported to the construction site and assembled to an entity by welded or bolted joints[3]. Therefore, the design of joints is the most critical part in the whole design process of a steel structure.

Many researches on the design method of prefabricated beam-column joints are conducted through theoretical or experimental methods. Li G. Q. [4] introduced an extended end-plate joint with single bolts and conducted single-direction-load tests to obtain the bending moment-angle curves and failure modes of specimens, by which the yield line models of columns are raised and the flexural capacity of joint are calculated according to the yield line theory and the principle of virtual work, respectively. ConXL joint is a new type of fabricated steel structure joint used for multi-high-rise buildings developed by ConXtech company, which has been obtained and recommended by the ANSI/AISC 358-10 with explicit stipulation of detailing requirements and calculation methods[5-7]. In the standard for design of steel structures (GB 50017-2017)[8], detailing requirements and calculation methods are also stipulated to some widely-used joints as a basic guideline. However, with the innovation of prefabricated joints, different or new methods must be applied or raised according to the stress analysis of joints through experimental and numerical methods. In this paper, a new type of fully prefabricated beam-column joints is put forward and corresponding design calculation methods are given to provide a certain reference for the calculation of joints.
2. Joint design

2.1. Joint structure
As presented in Figure 1, the new type of beam-column joint used for assembled steel structure is composed of rectangular tube column, H-beam, channel plate, angle iron, T-plate and high-strength bolt. Welded rectangular steel tube column and H-shaped steel beam are connected by 10.9-grade friction-type high-strength bolts, and all components are produced with Q345B steel.

In the design conception, the high-strength bolts near flanges mainly bear the bending moment transmitted through channel plate. The shearing force of beam web is delivered by the channel plate web and carried on by both the angle iron and bolts, further passing to the column. Meanwhile, the hoop formed by angle iron, T-plate and channel plate can actively restrain the column walls.

2.2. Design method
The checking calculation contents are defined through the experimental failure modes. As shown in Figure 2, the failure modes are mainly concreted in the destruction of welds between the beam end and channel plate, the tensile failure of bending bolts in the flange of channel plate and the bending and shearing failure of channel plate web. Therefore, the main checking calculation contents include the welds in beam end, the high-strength bolts in the channel plate web and the dimension of channel plate.

The calculation of welds in beam end is conducted by using some calculation assumption and according to the above-presented failure modes. The beam flange bears bending moment while shearing force is imposed on the welds in beam web. Besides, penetrated butt welds are adopted to the beam end and fillet welds to the connection between the webs of beam and channel plate. Therefore, only the shearing capacity of fillet welds between webs should be calculated by

\[ V_{\text{max}} = 2h_w t_w f_{\text{w}}^{\text{f}} \]  

where \( V_{\text{max}} \) is the maximum shear capacity, \( h_w \) is the effective length of welds, \( t_w \) is the effective width of welds and \( f_{\text{w}}^{\text{f}} \) is the design value of tensile strength.
The flexural and shear bolts in the joints are all frictional high-strength bolts with a diameter from 20 to 30mm. According to the principle that the bearing capacity of bolts should not be lower than that of beams, the tensile and shear strength of flexural and shear bolts are calculated respectively.

The high strength bolts in the flange of channel plate are designed to bear all the bending moment imposed on the joint. Therefore, the tensile ability of high-strength bolts is calculated to estimate that of the whole joint. Because the channel plate web was separated under the bending moment in the loading process while the flange was not, the neutral axis of bolts is assumed to be located at the geometric centre of channel plate. The arrangement of bolts in the channel plate flange is presented as Figure 3.

Figure 3. Arrangement of bolts in the channel plate flange

The tensile capacity of bolts can be calculated by

\[
N^b_T \geq \frac{M y_i}{2m \sin 45^\circ \sum y_i^2 \gamma_{RE}}
\]

(2)

\[
N^b_{tu} \geq \frac{M u y_i}{2m \sin 45^\circ \sum y_i^2}
\]

(3)

where \(N^b_T\) is the design value of tensile capacity of single bolt, \(\gamma_{RE}\) is the seismic adjustment coefficient of bearing capacity, \(M\) is the design value of beam end bending moment, \(m\) values 2, \(y_1\) equals to \(m_1\), \(y_2\) equals to \(m_1 + m_2\), \(N^b_{tu}\) is the ultimate tensile capacity of single bolt and \(M_u\) is the plastic bending moment value of the whole beam section.

High-strength bolts in the channel plate web and angle irons welded in the four corners of column bear the shearing force together. Therefore, the shearing capacity of bolts can be calculated by

\[
(n N^b_v + N)/\gamma_{RE} \geq V
\]

(4)

\[
n(N^b_{vu}, N^b_{cu})_{min} + N \geq V_u
\]

(5)

where \(n\) is the number of shearing bolts, \(N^b_v\) is the design value of shearing capacity of single bolt, \(N\) is the shearing capacity of fillet welds, \(V\) is the design value of beam end shear, \(N^b_{vu}\) is the ultimate shearing capacity of single bolt, \(N^b_{cu}\) is ultimate pressure-bearing capacity of connected plates and \(V_u = 0.58h_{wb}t_{wb} f_u\) (\(h_{wb}\) and \(t_{wb}\) are the height and thickness of beam web, respectively).

The thickness of channel plate is critical to the performance of joint. According to the experimental results, the stress in the channel plate web near the beam flange is the maximum and tends to decline along the flange of channel plate, which is at a 45-degree angle with the web. Taken the 4 bolts in the corner of flange as a integral one, then the channel plate can be considered as an extended end plate to be calculated, as shown in Figure 4. Therefore, the thickness of channel plate can be defined based on related specifications[9-11].

Figure 4. Transformation of channel plate to end plate

At the same time, the thickness of channel plate can be calculated by
\[
t_{eq} \geq \eta \frac{6e_{f}N_{t1}}{b_{ep} f / \gamma_{RE}} \\
t_{eq} \geq \eta \frac{4e_{f}N_{t2}}{b_{ep} f_{u}}
\]  
(6) 
(7)

where \( t_{eq} \) is the thickness of channel plate, \( \eta \) is the increase coefficient, \( e_{f} \) is the the average distance between the beam flange edge and the first row of bolts on both sides, \( b_{ep} \) is the width of beam flange, \( N_{t1} \) is the tension value of single bolt calculated by design bending moment, \( N_{t2} \) is the tension value of single bolt when the plastic hinge appears, \( f \) and \( f_{u} \) are respectively the design strength value and minimum ultimate tension value of end plate, respectively.

According to the principle of strong column and weak beam, column cannot fail before beam fails. The bearing capacity of joint should be calculated by

\[
\sum W_{pc}(f_{yc} - N/A_{c}) \geq \eta \sum W_{pb} f_{yb}
\]  
(8)

where \( W_{pc} \) and \( W_{pb} \) are respectively the plastic modulus of column and beam, \( f_{yc} \) and \( f_{yb} \) are respectively the yield strengths of column and beam, \( A_{c} \) is the combined seismic axial pressure, \( A_{c} \) is the section area of column and \( \eta \) is the strong column coefficient.

Besides, the joint with rectangular tube column should also be checked by

\[
t_{w} \geq (h_{b} + h_{c})/90
\]  
(9)

\[
(M_{b1} + M_{b2})/V_{p} \leq (4/3)f_{y}/\gamma_{RE}
\]  
(10)

\[
V_{p} = 1.8h_{b1}h_{c1}t_{w}
\]  
(11)

where \( t_{w} \) is the thickness of column web, \( h_{b} \) and \( h_{c} \) are respectively the centre line distances between the flanges of beam and column in the thickness direction, \( M_{b1} \) and \( M_{b2} \) are respectively the bending moment design value of beams in both sides of joint, \( V_{p} \) is the volume of joint, \( f_{y} \) is the design value of shearing strength and \( \gamma_{RE} \) is the anti-seismic adjustment coefficient.

3. Detailing requirements

The welding of beam and channel plate should be carried out in factories according to the welding methods, technological parameters and welding sequence stipulated in the process documents prepared in advance and conform to the provisions of the current national welding regulations.

The bending curve between channel plate and column flange should be strictly controlled to reduce the gap. Because a part of bolts tends to loosen under the cyclic load according to the tests, it’s important to control the machining accuracy to guarantee the effectiveness of joints’ working performance.

When the thickness of channel plate exceeds 30mm, ultrasonic inspection should be carried out on the base material before welding, and reasonable welding groove and sequence, preheating and post-heat treatment should be adopted to prevent the laminar tearing in the thickness direction.

Fillet welds are used to connect the four corners of column with the iron angle and to connect the T-plate with the channel plate web.

Any machining deformation of members should be corrected, especially the deformation of web and flange of channel plate, which directly affects the bonding degree between bolts and contact surface and the connection stiffness of joint.

The bolt holes shall be produced by drilling tool, and the friction surfaces shall be protected by some measures. During the installation of high strength bolts, pre-tension shall be applied from the four corners to the middle and in two stages gradually.
4. Conclusion
This paper introduces the design method and detailing requirements of a new type beam-column joints for fully assembled steel structures according to experimental results and related standards. And following suggestions for the development of steel structural joints are put forward:

1) The checking calculation of innovative joints should not only agree with the stress distribution and failure modes obtained through FEM analysis and experiments but also meet the detailing requirements of standards, which are the fundamental references for the design of all structures.

2) Welds exist in all connections of steel structures, even in the so-called fully bolted joints. High quality of welds is the most important to develop the full performance of steel structures. Therefore, the quantity of welds should be reduced as soon as possible in the design of joints and the welds between members of joints must be detected and improved to decrease the failure risk of joints, which also meets the design principle of strong joints and weak members.

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