Study on optimal design of a new type of beam-column assembled rigid joint

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Abstract. With the progress of engineering technology, steel structure has become the mainstream structural form of construction engineering, and beam column composite structure is the most commonly used connection form in steel structure buildings. In order to improve the design and construction performance of beam-column joint, a new type of beam-column assembled rigid joint is proposed and its parameter optimization is analysed based on equal strength design method and finite element software. The results show that the new beam-column assembled rigid joint has excellent performance for ductility and energy-dissipating capacity and the joints and splice plates can both meet strength requirements. The number of bolts and the length of cantilever beam have great influence on the ultimate bearing capacity and ductility of the joint. The new type of beam-column assembled joint is easy to construct and has good mechanical properties, and its ductility and elastoplasticity are better than those of ordinary joints without splicing.

1. Introduction
With the improvement of national economic level and engineering technology, steel structure has become the mainstream structure. At present, beam-column composite structure is common in steel structure [1]. At first, steel columns and beams are prefabricated in processing factory and are connected together by high strength bolts or welding in construction site for beam-column composite structure [2]. This method requires high construction conditions with slow speed and is easy to cause fire with welding on site. The composite structure has poor seismic performance and little ductility with weld, which needs to add auxiliary construction technology or local strengthening members to meet the requirements of strength, stiffness and stability. This will cause waste of resources and extension of construction period, which goes against the original intention of green building. So the steel reinforced concrete composite structure with cantilever beam is widely used. It can reduce in-situ welding process and construction hazards, and can reduce the requirements of this structure on construction site conditions with cantilever beam and steel column being welded together first in the processing factory, and splicing with steel beam by bolts on site [3].

Gu Qiang studied the hysteretic behavior of beam-column joints and obtained some useful conclusions [4]. Xia Junwu et al. analysed the elastic-plastic bearing capacity of splice joint for steel reinforced concrete composite structure with cantilever beam [5]. Zhou Dianwen compared the mechanical properties between spliced joint with cantilever beam and ordinary joint [6]. Sheikh-Ibrahim
et al. analysed distribution of shear force in flange splicing and web splicing to study the calculation method of shear eccentricity [7]. In generally, the number of bolts and their holes is large, and the section is weakened in the joint of cantilever beam, which is demanding for construction quality of welding at the splice. The ductility of welds and bolted connections are poor under earthquake, which requires high technical requirements for construction workers. In this paper, a new type of beam-column assembled rigid joint with setting staggered splice plate to reduce bolts at beam end is studied. In order to improve the ductility, horizontal and vertical stiffeners are added based on outward displacement of reinforced plastic hinge at beam-column joints. The construction layout of node core area can be optimized, and the accurate position of beams, columns, splice plates, stiffeners, bolts and welds can be obtained in advance to realize visual construction by using BIM to build three-dimensional model. This new joint can reduce construction difficulty and cost, shorten construction period, improve construction efficiency and material utilization, improve structural ductility, and meet the structural safety and economic performance.

2. Analysis method

2.1. Equal strength design method
At present, there are four common methods of equal strength design method, practical design method, accurate design method and simplified design method to analyse beam-column splicing. The working principle of equal strength design method adopted in this paper is that the net section of beam flange and web at the joint is equal in strength, which is helpful to ensure the ductility of joints. Full penetration groove welding is applied at the flange of splice beam. The checking calculation of joint strength for weld is not necessary with weld and plate being considered as equal strength and the web bearing all shear force. The number of high strength bolts is determined according to their shear bearing capacity being equal to the net section shear bearing capacity of web. The equal strength design method based on cross-section size of the beam does not consider the design internal force and the joint form is relatively unified, which is easy to process and manufacture.

2.2. Constitutive relation
The finite element solid model was established by ANSYS with three-fold-line model considering strengthening and descending. The stress-strain relationship of steel was as shown in Fig. 1. Steel of Q235 and E43 was respectively selected for beam and column, and welding rod. Grade 10.9 high strength bolt of M20 with a diameter of 21.5mm and anti sliding coefficient of 0.4 was adopted[8]. All degrees of freedom at column end were subject to fixed constraints, Y-direction displacement was coupled at beam end and X-direction restraint was applied where 1.6m away from column flange.

Beam and column was simulated by solid element, and the bolt was simulated by sweeping element. The contact pairs between flange splice plate and beam flange, and between web splice plate and web were established with friction property of ignoring friction between bolt bar and hole.

![Stress-strain relationship](image-url)
2.3. Loading condition
The pretension of 155 kN was applied first on the bolt, and then the cyclic displacement load was applied at the beam end. The yield displacement was 20 mm and the total displacement load applied in multiple substeps was 80 mm. The initial displacement was 20% of the yield displacement, and the displacement increment of each stage was about 20% in this paper. One load cycled per stage before yielding and each load cycled two times with yield displacement increased by 2, 3 and 4 times in turn after yielding. The loading conditions were as shown in Tab. 1.

| Load step | Displacement (mm) | Number of cycles | Angle of beam end (rad) |
|-----------|-------------------|------------------|-------------------------|
| 1         | ±4                | 1                | 0.001                   |
| 2         | ±8                | 1                | 0.002                   |
| 3         | ±12               | 1                | 0.005                   |
| 4         | ±16               | 1                | 0.007                   |
| 5         | ±20               | 1                | 0.008                   |
| 6         | ±40               | 2                | 0.018                   |
| 7         | ±60               | 2                | 0.028                   |
| 8         | ±80               | 2                | 0.038                   |

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3.1. Design scheme
All beams and columns were made of H-shaped steel. The connecting bolts between upper and lower flange cover plates of the beam was single shear and that of the web plate was double shear. The geometric diagram of the component was as shown in Fig. 2.

| Analysis parameters | Number of scheme | Number of bolts | Length of cantilever beam/m | Pretension of high-strength bolts/kN | Friction coefficient |
|---------------------|------------------|-----------------|-----------------------------|------------------------------------|---------------------|
| Number of bolts     | 1-1              | 10              | 0.7                         | 155                                | 0.4                 |
|                     | 1-2              | 6               | 0.7                         | 155                                | 0.4                 |
|                     | 1-3              | 8               | 0.7                         | 155                                | 0.4                 |
|                     | 1-4              | 12              | 0.7                         | 155                                | 0.4                 |
|          | Length of cantilever beam | Pretension of high-strength bolts/kN | Friction coefficient |
|----------|--------------------------|--------------------------------------|---------------------|
| 2-1      | 6                        | 0.7                                  | 155                 |
| 2-2      | 6                        | 0.5                                  | 155                 |
| 2-3      | 6                        | 0.6                                  | 155                 |
| 2-4      | 6                        | 0.65                                 | 155                 |
| 2-5      | 6                        | 0.75                                 | 155                 |
| 2-6      | 6                        | 0.8                                  | 155                 |
| 2-7      | 6                        | 0.85                                 | 155                 |
| 3-1      | 6                        | 0.7                                  | 155                 |
| 3-2      | 6                        | 0.7                                  | 93                  |
| 3-3      | 6                        | 0.7                                  | 124                 |
| 3-4      | 6                        | 0.7                                  | 186                 |
| 3-5      | 6                        | 0.7                                  | 217                 |
| 4-1      | 6                        | 0.7                                  | 155                 |
| 4-2      | 6                        | 0.7                                  | 155                 |
| 4-3      | 6                        | 0.7                                  | 155                 |

3.2. Parameter optimization analysis

3.2.1. Stress analysis of key parts

(1) Stress of upper flange along length direction of beam

Fig. 3 showed the results of stress of upper flange along the length direction of the beam.

![Stress of upper flange along length direction of beam](a)

![Stress of upper flange along length direction of beam](b)

![Stress of upper flange along length direction of beam](c)

![Stress of upper flange along length direction of beam](d)

Fig.3 Stress of upper flange along length direction of beam

The analysis results of influence of number of bolts on stress of upper flange along the length direction of the beam showed that the stress distribution of the upper flange along the length of the beam with different number of bolts was basically the same. The stress of scheme 1-3 was greater than that of
other members, and the maximum stress was located at the weld joint of beam-column. The closer to the joint, the greater the stress, and the increase range of scheme 1-3 was larger than that of other members.

The analysis results of influence of length of cantilever beam on stress of upper flange along the length direction of the beam showed that the stress distribution of the upper flange along the length of the beam with different length of cantilever beam was basically the same. The stress of scheme 2-2 was greater than that of other members, and the maximum stress was about 600 MPa, which was located at the joint of beam-column.

The analysis results of influence of pretension of high-strength bolts showed that the stress distribution of upper flange along beam length had nothing to do with pretension of high-strength bolts. The stress 300 mm away from the joint of beam-column of scheme 3-5 was up to 500 MPa. The stress of 3-2, 3-3 and 3-4 were basically unchanged and was close to scheme 3-1.

The analysis results of influence of friction coefficient showed that the stress distribution of upper flange along the length of the beam had nothing to do with friction coefficient. The stress 1000 mm away from the joint of beam-column of scheme 4-1 was up to 300 MPa which was greater than that of other schemes. The stress of scheme 4-2 and scheme 4-3 changed little.

It can be seen that the number of bolts and the length of the cantilever beam had a certain influence on the change of stress of upper flange along the length direction of the beam.

(2) Stress of beam root along width direction of beam upper flange

Fig. 4 showed the results of stress of beam root along width direction of beam upper flange.

The analysis results of influence of number of bolts showed that the stress distribution of beam root along width direction of upper flange of beam between scheme 1-4 and scheme 1-1 was consistent which tended to be big on both sides and small in the middle. The stress of scheme 1-4 increased gradually on the whole and the maximum stress was 1125 MPa. The less the number of bolts, the greater the joint stress. The stress of scheme 1-3 in the middle of the beam flange decreased and was about 500 MPa.
The analysis results of influence of length of cantilever beam showed that the stress distribution of the beam root along width of upper flange with different cantilever length was basically the same. The stress at the end of upper flange of scheme 2-2 was the largest and was up to 1000 MPa.

The analysis results of influence of pretension of high-strength bolts showed that the pretension of high strength bolts had little effect on stress distribution of the root along width direction of upper flange. The stress at the middle of beam root of scheme 3-3 along width direction of upper flange of the beam was reduced by 10 MPa by reducing bolt pretension.

The analysis results of influence of friction coefficient showed that the stress distribution of the beam root with different friction coefficients along width direction of upper flange was similar, which was larger on both sides and smaller in the middle.

It can be seen that the number of cover plate bolts and the length of cantilever section had an impact on stress distribution of joint at the root along width direction of upper flange of the beam.

3.2.2. Ductility coefficient

Ductility can be characterized by load-deformation curve and ductility coefficient, and ductility coefficient can be calculated according to the follows:

\[
\mu = \frac{\delta_u}{\sigma_y}
\]  

(1)

Where, \(\delta_u\) and \(\sigma_y\) respectively denotes the ultimate displacement and yield displacement.

Fig. 5 showed the results of ductility factor of different design schemes.

It can be seen from Fig. 5 that the number of bolts and the length of cantilever beam had an effect on the ductility of the joint. The ductility coefficient of scheme 4-2 and scheme 4-3 was less than 3, which can not meet ductility requirements. The other design schemes can meet the ductility requirements. The ductility coefficients of scheme 1-2 and 1-3 were obviously smaller than those of scheme 1-1.

The results showed that the less the number of bolts, the smaller the ductility of the joint.
3.2.3. Plastic angle and total angle of beam end

Plastic rotation is one of the important indexes to evaluate energy dissipation capacity of beam-column joint[3]. Generally, the minimum standard of good seismic performance is rad plastic rotation of 3% and rad total rotation of 5%. Plastic angle and total angle can be calculated according to the follows:

$$\theta_{\text{total}} = \frac{\delta}{l_0}$$  \hspace{1cm} (2)

$$\theta_p = \frac{\delta_0 - \delta_e}{l_0}$$  \hspace{1cm} (3)

$$\delta_e = \frac{P l_0}{3EI}$$  \hspace{1cm} (4)

Where, $\delta_0$ denotes the reading of displacement meter at beam end, $l_0$ denotes the distance from loading end to column center, $\delta_e$ denotes the displacement of beam end caused by elastic deformation, $P$ denotes the load at beam end.

The results of plastic angle and total rotation angle of each scheme were as shown in Fig. 6.

![Fig.6 Analysis of plastic angle and total angle](image)

The results showed that the number of bolts, the length of cantilever beam, the pretension of high-strength bolts and friction coefficient had a certain impact on seismic performance of the joint. The plastic angle and total angle of the joint can basically meet the ductility requirements after changing the number of bolts and the length of cantilever beam. The energy consumption of scheme 1-2 and scheme 1-3 were slightly lower than that of scheme 1-1, and the energy consumption of scheme 1-4 was slightly higher than that of scheme 1-1.

3.2.4. Equivalent viscous damping coefficient

At present, equivalent viscous damping coefficient [3] is the main evaluation index of energy dissipation capacity and seismic capacity of steel frame structure. The equivalent viscous damping coefficient of different design schemes were shown in Fig. 7.
The calculation results of equivalent viscous damping coefficient of different design schemes were shown in Fig. 7. The equivalent viscous damping coefficient of design scheme 1-2 was smaller. The results showed that reducing the number of cover plate bolts had a great adverse effect on seismic performance of the joint.

4. Conclusion
In order to improve the design and construction performance of beam-column joint, a new type of beam-column assembled rigid joint is proposed and its parameter optimization is analysed based on equal strength design method and finite element software in this paper and the main conclusions are as follows:

1) The ductility and energy dissipation capacity of the scheme based on equal strength design method are better, and the strength of joints and splice plates can meet the requirements. The number of bolts and the length of cantilever beam have influence on ultimate bearing capacity and ductility of the joint.

2) The ultimate bearing capacity of the joint decreases slightly with the decrease of the number of bolts, but the energy can be dissipated by bolt slip in the splicing area and plastic deformation of the splicing plate. The ductility and ultimate bearing capacity of the joints are improved a little with the increase of the number of bolts.

3) The new type of beam-column assembled joint is convenient for construction and its mechanical properties, ductility and elastic-plastic behavior of new beam-column assembled joint is better than that of ordinary joint without splicing.

4) At present, there are three widely used methods for elastic-plastic analysis under earthquake. Different methods can be compared to achieve the most suitable elastic-plastic theoretical model for steel composite structure bridge, which needs to be further studied.

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