Finite Element Analysis of Mechanical Behavior of Assembled SRC Beam- CFST Column Composite Frame

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Abstract. Prefabricated buildings have the advantages of good component quality, fast construction speed and less construction waste, which is an important measure to implement ecological civilization, save resources, protect the environment and reduce pollution. The composite structure of section steel and concrete gives full play to the advantages of light weight, high strength, assembling construction and high recovery rate of steel. However, the construction method of assembly is still in the research stage. In order to explore the key problems in engineering application, such as mechanical performance, material behavior, failure phenomenon, connection design etc. of SRC beam-CFST column composite frame (hereinafter referred to as "composite frame"). On the basis of the experimental results of exterior joints in the early stage, the whole process mechanical behavior of composite frames under vertical load and horizontal low cyclic load is studied by using ABAQUS finite element analysis software. The research shows that the assembled connection mode has better static and seismic performance, and the material performance is fully utilized. The mechanical performance of the full welded and bolt-welded hybrid connection is similar. Increasing the thickness of the ring plate and the height of the beam section can improve the bearing capacity and energy dissipation capacity.

Keywords. Prefabricated building; SRC beam; CFST column; Composite frame; Finite element analysis

1. Introduction

Assembled building components are produced mechanically in factories or project factory. It can be completed by reliable connection after being hoisted in place on site. It has the advantages of good component quality and fast construction speed, reduces construction noise pollution and construction waste, and is an important measure to implement ecological civilization thought, save resources and protect the environment. In recent years, under the requirements of improving the development quality, protecting the ecological environment and promoting the industrialization of buildings in China, prefabricated buildings have been widely popularized.

In September 2016, the State Council executive meeting announced the decision to vigorously develop prefabricated buildings. Vigorously developing prefabricated buildings such as steel structures and concrete can achieve the goals of developing new industries of energy conservation and environmental protection. Therefore, relevant departments and industries are required to improve relevant standards and specifications, promote integrated design, industrial production and assembly...
construction, and encourage the research and development of applicable technologies, equipment and machines.

In August 2020, the Ministry of Housing and Urban-Rural Development and other departments issued "Several Opinions on Accelerating the Industrialization Development of New Buildings". The article is clear: promote standardized design and promote prefabricated building system; Promote the industrial production and application of section steel and concrete members and other general components.

Steel-concrete composite structure gives full play to the advantages of light weight, high strength, assembly construction and high recovery rate of steel. The use of concrete makes up for the poor stability and fire resistance of pure steel structures, and has higher bearing capacity and better seismic performance than traditional RC structures. At present, it has been widely used in long-span, high-rise and super-high-rise buildings. The application range of prefabricated buildings will be expanded when the steel-concrete composite structure is constructed in an assembled way. Therefore, it is the key to realize engineering application to solve the assembly connection mode of composite structure and study its mechanical performance.[1-6]

2. Research status of fabricated steel-concrete composite structure

Since 2010, the state and industry have successively issued relevant standards and regulations, such as Technical Specification for Prefabricated Concrete Structures, Technical Standard for Prefabricated Concrete Buildings, Technical Standard for Prefabricated Steel Structure Buildings, and Technical Standard for Prefabricated Steel Structure Residential Buildings etc.

Wang P [7] designed a new type of all-bolt-connected through-inner diaphragm joints between H-beam and CFST column, and compared the seismic performance of the traditional diaphragm through joint, and extended analysis was carried out by finite element software with the number of flange bolts as the variable. The research shows that both the new joint and the traditional joint have good seismic performance, and the new joint is simple in structure and more conducive to manufacture and assembly.

Wei J et al. [8] assembled CFST column with steel beams using channel steel and cover plates. Seismic experiment shows that this kind of joint has good mechanical performance, and the bearing capacity of the joint increases with the increase of cover thickness, but the ductility decreases.

Rong X et al. [9] conducted an experimental study on the seismic performance of the joints between CFST column and H-shaped steel beams, and concluded that the seismic performance of bottom-flange bolted and top-flange-welded connections is similar to that of full bolt connections, and increasing the beam section height can improve the bearing capacity, stiffness and energy dissipation capacity of the joints.

Our research group proposed a composite frame of CFST columns and H-shaped SRC beams (hereinafter referred to as "composite frame"), in which steel beams are wrapped with concrete to improve the stability and fire resistance of beams. Through experiments and finite element software analysis, the joint and the whole mechanical behavior of composite frame are studied, which provides engineering application reference for the design and application of this kind of structure.

3. Experimental study on seismic behavior of side joints of assembled SRC beam- CFST column composite frame

Our research group Liu M [10] conducted an experimental study on the seismic behavior of five exterior joints of H-shaped SRC beams and CFST columns in the early stage. The H-shaped steel in the beams is connected with the square steel tubular columns through polygonal outer ring plates and end vertical plates. Design parameters of the specimen are shown in Table 1.
Table 1. Design parameters of combined frame joints.

| Node number | Connection position /mm | Connection mode               | Stirrup spacing in assembly area /mm |
|-------------|-------------------------|--------------------------------|--------------------------------------|
| JD1         | Column edge 170         | Bolt welding mixing           | 50                                   |
| JD2         | Column edge 170         | Bolt welding mixing           | 175                                  |
| JD3         | Column edge 170         | Pure bolt                     | 50                                   |
| JD4         | Column edge 320         | Pure bolt                     | 50                                   |
| JD5         | Column edge 320         | Bolt welding mixing           | 50                                   |

Failure phenomenon: the first crack (bending type) appears at the interface of concrete in the assembly area, and the subsequent cracks gradually turn into bending shear type cracks and concentrate at the junction of beam and column, and shear inclined cracks appear in the concrete between ring plates. There are two longitudinal compression cracks at the top and bottom of JD1 column side beam, and the ring plate has obvious bending shear deformation. The concrete in JD2 steel pipe is crushed, and the steel pipe has 3mm buckling deformation. The ultimate displacement of JD3 is smaller than the former two, and the bearing capacity decreases rapidly. There is a deep bending-shear crack between JD4 ring plates, the deformation of the ring plates is small. The deformation of JD5 ring plate is the most obvious.

The research shows that most joints have good energy consumption and ductility. There is no obvious damage in the assembly area, which indicates that this kind of fabricated connection can effectively transfer force. Comparison of joint design variables: (1) The location of bolted and welded hybrid connection has no obvious influence on seismic performance. (2) When connecting near the column end, the bearing capacity and ductility of bolt-welded hybrid connection are obviously improved. (3) The increase of stirrup spacing will make the joints brittle. (4) The location of pure bolt connection has certain influence on seismic performance.

4. Finite element analysis of assembled composite frame

4.1. Material, size and connection mode of composite frame

The finite element models of four 1:1 square CFST columns and H-shaped SRC beams are established by ABAQUS software, and the component dimensions refer to the assembly project of Tongji Yincheng (Hezhou) Industry-University-Research Base. The column height is 3.6m and the beam span is 6.3m. Four composite frame specimens PF1–PF4 were designed with the connection mode of assembly area, beam section height and ring plate thickness as variables. The grade of section steel is Q235B, the size of square steel tube column is 600×600×30×30, the concrete strength of prefabricated part is C35, and the post-cast concrete is C45. Within the beam, HRB400 Φ12 erection bar and HPB235 Φ6 stirrup are provided. In the assembly area, the flange of H-shaped steel is connected with the reinforcing ring, and the web plate is connected with the end vertical plate, which are welded to one side of the square steel tube column. The vertical plates at PF3 and PF4 ends are connected with the H-shaped steel web through eight M16 high-strength bolts of grade 8.8. Other design parameters are shown in Table 2, and steel connection of PF3 joint is shown in Figure 3.
Table 2. Design parameters of combined frame joints.

| Frame number | H-beam size/mm | Beam size/mm | Connection mode of assembly area | Thickness of reinforcing ring/mm |
|--------------|----------------|--------------|----------------------------------|----------------------------------|
| PF1          | 600×30×12×20   | 750×350      | Weld                             | 20                               |
| PF2          | 500×30×12×20   | 600×350      | Weld                             | 20                               |
| PF3          | 600×30×12×20   | 750×350      | Flange welding, web bolt connection | 20                              |
| PF4          | 600×30×12×20   | 750×350      | Flange welding, web bolt connection | 24                              |

4.2. Composite frame finite element model

Concrete materials adopt the constitutive relation specified in Code for Design of Concrete Structures and the plastic damage model of ABAQUS. The stress-strain relationship of section steel, reinforcing steel bar and high-strength bolt adopts the bilinear model. Except that truss elements are used for reinforcing bars, other members adopt solid elements. The intersection of section steel and concrete cuts the concrete, and steel bars and bolts are embedded in the concrete. In order to prevent concrete from being damaged in advance under vertical load, a rigid cushion block is set at the three-equal-division point of the beam, and the upper surface of the cushion block is coupled with the loading point.

According to the limit in Code for Design of Composite Structures, the vertical displacement of loading point is set to 50mm, and the vertical bearing capacity is determined by the reaction force of calculation results. Horizontal low-cycle reciprocating action is applied by point-surface coupling. The loading surface is selected between the two ring plates on the right side of the column. According to the Code for Design of Concrete Structures of Tall Buildings, the displacement increment is 7mm, and each loading stage is cycled three times. The bottom of the column is restrained by point-to-surface coupling. The grid division of PF4 frame, high strength bolt and cover plate is shown in Figure 4.

5. Analysis of finite element calculation results

5.1. Vertical bearing capacity

It can be seen from the curve of the relationship between the sum of the vertical reaction force p and the deflection δ in the mid-span of the beam that PF2 has the lowest bearing capacity (max 4146.3kN) and bending stiffness. Compared with PF1 (max 5305.2kN), the height of H-beam is 100mm less, the height of concrete is 150mm less, and the maximum vertical bearing capacity is 28% lower. The bearing capacity of PF1 and PF3 (max 5412.9kN) is similar, which shows that the form of connection has little influence on the vertical bearing capacity and stiffness. The maximum vertical bearing capacity of PF4 is 5622.9kN, which is about 3.88% higher than that of PF3, indicating that the increase of ring plate thickness can improve the vertical static load bearing capacity appropriately. According to the stress nephogram and deformation, the failure process of the four frames is similar,
and the plastic hinge is located in the composite stress zone of bending and shearing at the beam end. The column has no obvious deformation, and the stress of the corner bolt near the joint is the largest.

5.2. Seismic performance

5.2.1. Destruction phenomenon. The failure process and stress distribution of the four frames are similar, which shows that the connection mode has little influence on the overall mechanical performance of the frames. It can be seen from the stress nephogram of PF3 section steel at 4δ (Figure 6) that the stress at the foot of the column is large, and the stress distribution in the joint and assembly connection area is complex. During failure, the upper end of the steel tube column is greatly deformed (Figure 7). The concrete at the beam end in the joint area is cracked and crushed in reciprocating motion, and the joint between the ring plate and the H-shaped steel flange is lengthened and the thickness becomes thinner, which indicates that the ring plate and steel pipe have influence on the deformation of the joint area and the seismic performance of the frame, and there is obvious deformation omen before the bearing capacity of the frame decreases, which belongs to plastic failure.

5.2.2. Hysteresis curve. Figure 8 shows the hysteretic curve of the test frame. All the four frames are full fusiform and have large lateral stiffness. After 3A cycling, the strength begins to decrease, which belongs to ductile failure, indicating that the fabricated composite frame has good seismic performance. In order to analyze the influence of three variables on the seismic performance of the frame, the hysteretic curves of the frame are divided into three groups, and the comparative analysis is as follows:

(1) The horizontal reaction force of PF1 is greater than PF2, and the hysteretic curve is fuller, which shows that increasing the beam height can improve the frame stiffness and energy dissipation capacity, and has obvious influence on the seismic performance.

(2) There is little difference between PF1 and PF3 hysteretic curves, which shows that the connection mode has little influence on seismic performance. The bolt welding hybrid connection reduces the manual welding on site, and reduces the influence of welding residual stress and deformation on the mechanical performance of the frame, so the joint construction quality is easier to guarantee.

(3) PF4 ring plate is 4mm thicker than PF3, and the maximum bearing capacity in hysteretic curve is improved, but the stiffness and fullness of hysteretic ring have little difference. Therefore, it is suggested that the ring plate should have the same thickness as the H-beam flange to reduce the stress concentration caused by the change of plate thickness.

![Figure 5. Frame vertical reaction-displacement relationship](image-url)
5.2.3. **Skeleton curve.** By analyzing the skeleton curve comparison diagram (Figure 9), it can be seen that the seismic bearing capacity of the frame decreases slowly in the later stage of loading. This shows that the prefabricated connection of SRC beams and CFST columns through outer ring plates can ensure that the frame does not appear brittle failure. Compared with other frames, PF2 reduces the beam height, so the lateral stiffness and bearing capacity are the lowest. The skeleton curves of the other three frames are similar. This shows that the two connection modes and the thickness of the ring plate have no obvious influence on the seismic stiffness and bearing capacity of the frame.
5.2.4. Bearing capacity reduction coefficient. The damage accumulation degree and subsequent bearing capacity can be obtained by analyzing the bearing capacity reduction coefficient of the second and third cycles of each loading stage compared with the previous cycle. The average value of bearing capacity reduction coefficient of frame in positive and negative loading directions is shown in Table 3. It can be seen from the table that the bearing capacity of the first two loading stages has almost no attenuation, which indicates that the composite frame has a good strength reserve before reaching the peak load. After the third loading stage, the accumulated damage of the frame began to reduce the bearing capacity. Frames with larger beam heights (PF1, PF3, PF4) have higher bearing capacity, and more materials enter plasticity, so the bearing capacity declines more. Connection mode and cover plate thickness have no obvious influence on bearing capacity reduction coefficient.

![Figure 9. Skeleton curves.](image)

| Load level | Cycles | PF1 | PF2 | PF3 | PF4 |
|------------|--------|-----|-----|-----|-----|
| 1Δ=7mm     | 2      | 1.07| 1.07| 1.06| 1.07|
|            | 3      | 1.00| 1.01| 1.02| 0.99|
| 2Δ=14mm    | 2      | 1.09| 1.07| 1.08| 1.08|
|            | 3      | 1.01| 1.00| 1.01| 1.01|
| 3Δ=21mm    | 2      | 0.97| 0.99| 0.97| 0.97|
| (Peak load)| 3      | 0.97| 0.98| 0.98| 0.97|
| 4Δ=28mm    | 2      | 0.96| 0.96| 0.96| 0.96|
|            | 3      | 0.94| 0.96| 0.95| 0.95|

6. Conclusions
(1) After the bearing capacity of composite frame is reduced, the upper end of square steel tube column and ring plate have obvious deformation, which belongs to plastic failure mode.
(2) The hysteretic curve of the composite frame under horizontal low cyclic loading is full fusiform, and the lateral stiffness is large.
(3) Among the design variables, the beam section height has a great influence on the vertical and horizontal bearing capacity, lateral stiffness and bearing capacity reduction coefficient of the frame. The thickness of the ring plate has a slight influence on the mechanical performance, and the connection form has no obvious influence.
(4) Compared with pure welding, the quality of on-site bolt welding hybrid connection is easier to ensure and the possibility of welding quality defects is reduced. The thickness of the ring plate should be the same as that of the beam flange to reduce the construction difficulty and stress concentration.
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