Nonlinear Numerical Analysis on Seismic Performance of New-type Outer Hoop Box Column Joints

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Abstract. The connection between the upper and lower structure is the key to seismic design of RC frame-lightweight steel mixed structure. This paper proposes a new type of outer hoop box column joint for this kind of mixed structure, which aims to strengthen the connection between exiting and new building, reduce the stiffness mutation and facilitate construct. In order to study the seismic performance of the new type of joint, the ABAQUS finite element software was used to carry out the numerical analysis of the new type of joint under the action of low-cycle cyclic loading with a 1/2 scale model, and the factors that affect the seismic performance were discussed in-depth. The results show that the hoop effect of the outer hoop steel plate strengthens the restraint on the core area of the joint and its surrounding members, which causes the plastic hinge position of the concrete beam to move outward, effectively protects the core area of the joint, and is beneficial to the bearing capacity of the new joint. Appropriately increasing the axial compression ratio can increase the bearing capacity, initial stiffness and yield displacement of the new joints to a certain extent.

Keywords. Outer hoop box column joint, RC frame-lightweight steel mixed structure, the axial compression ratio, energy dissipation capacity, seismic performance.

1. Instruction

The reinforced concrete (RC) frame-lightweight steel mixed structure can be built through increasing layer, which the top is single layer or multi-layer light steel structure, and the bottom is reinforced concrete frame. The research of this kind of mixed structure meets the requirements of my country's sustainable development strategy [1]. However, the stiffness and damping of the upper and lower parts are quite different [2]. How to ensure that the upper and lower structures work together in the earthquake and effectively transmit the seismic horizontal load to the vertical lateral force-resistant members [3-4], which places high requirements on the connection joints of the existing and new buildings. Therefore, the connection joints of the upper and lower structures are the key to the seismic design of this type of hybrid structure [5-6].

A new type of joint-the outer hoop box column joint for the RC frame-lightweight steel mixed structure is proposed in this paper [7], as is shown figure 1, to overcome the deficiencies of current technology and provide a new kind of assemble joint that have little effect on the residents’ life during construction, convenient for on-site installation, improve the efficiency of construction and the ability of the upper and lower structures to work together.

2. Establishment of Finite Element Model

The finite element model of ABAQUS's was established completely in accordance with the geometric
dimensions, production methods, boundary constraints, measured material properties, and loading system of the new outer hoop joint in the literature [8].

2.1. Specimen Design
The reinforcement and geometric dimensions of the specimen are shown in figure 2. The Q235B welded box section was used for upper steel column, the concrete grade was C30, and the diameters of stirrup, longitudinal reinforcement of beam and column were 8 mm, 12 mm, and 18 mm respectively.

![Figure 1. New type of outer hoop box column joint.](image1)

![Figure 2. Geometric size of specimen (JD-1).](image2)

2.2. The Material Constitutive Relation
Using the Von Mises yield criterion and related flow criteria, the constitutive relationship of steel and reinforcement were simulated by the multi-linear follow-up strengthening model. The specific values are shown in table 1 for the measured mechanical properties of steel and reinforcement.

The average compressive strength of the concrete test block was 32.17 MPa. The damage plasticity model (CDP model) provided by ABAQUS was used to simulate the mechanical properties of concrete materials [9].

![Table 1. Mechanical properties of steel reinforcements and steel](table1)

| Specification         | Material grade | Yield strength (Mpa) | Tensile strength (Mpa) | Rate of elongation |
|-----------------------|----------------|----------------------|------------------------|-------------------|
| Φ8                    | HPB300         | 332.57               | 489.10                 | 23.75%            |
| Φ12                   | HRB400         | 419.56               | 585.89                 | 33.33%            |
| Φ18                   | HRB400         | 458.64               | 629.93                 | 22.96%            |
| Steel plate of 12mm   | Q235           | 299.55               | 421.52                 | 28.89%            |
| Steel plate of 16mm   | Q235           | 262.67               | 395.57                 | 31.33%            |

2.3. Element Type, Interaction between Components and Meshing
Solid elements (C3D8R) were used to simulate the concrete and steel structure, and the linear truss element T3D2 was used to simulate the reinforcement model.

The separate modeling method was adopted, which the embedded regions were used to describe the relationship between reinforcement and concrete elements. In the experiment, chemical glue was used to fix the anchor bolts, so a binding constraint (Tie) was set to simulate this connection. A contact model consisting of the contact relationship in the normal direction and the bond-slip in the tangential direction was set between the anchor bolt, the column base plate, the outer hoop steel plate and the concrete to simulate friction [10].

The grid size of the concrete beams, columns and steel mesh was 60 mm, and the grid size of the remaining components was 20 mm. The cell meshing is shown in figure 3.
2.4. Boundary Constraints, Loading System

Boundary constraints were carried out according to the test loading device. The bottom end of the column was a fully fixed hinged support. The beam end was a sliding hinged support. The translational displacement and rotational displacement in two directions outside the plane of the loading head of the steel column were constrained.

Displacement-controlled loading was adopted. A vertical force of 175 kN was applied to the top of the steel column in a uniform load to simulate that the axial compression ratio of the box column was 0.16. A low-cycle repeated horizontal load was applied to the top of the steel column. The thrust was positive and the pulling force was negative. The yield displacement point was initially determined to be 24 mm by the hysteresis curve in the forward pushing process. The difference of displacement was 4mm and each grade was 1 time before yielding. After the yielding, the loading displacement was multiplied by the multiple of the yield displacement and each grade was loaded three times until the load value reached 85% of the ultimate load or the specimen was completely destroyed. Stop loading when it no longer changed.

3. Verification of the Correctness of the Finite Element Model

Using the same loading method as the test, the finite element analysis results were compared with the test results to verify the correctness of the finite element model.

3.1. $P$-$\Delta$ Hysteresis Curve under Cyclic Load

Figure 4 shows the column top load ($P$)-displacement ($\Delta$) hysteresis curve calculated by the finite element under the cyclic reciprocating load of the JD-1 specimen. Because the finite element could not truly simulate the damage performance of concrete materials and the slip of reinforcements, the $P$-$\Delta$ hysteresis curve of the theoretical calculation result was approximately a parallelogram, which was more full than the experimental result of literature [8], and the enclosed area was larger. In the elastic stage, the hysteresis curve showed a linear growth trend, the enclosed area was small, and the energy consumption of the specimen was weak. After entering the yield section, the bearing capacity increased slowly, the plastic deformation and the enclosed area of the hysteretic curve increased, and the specimen consumed more energy. With the increase of the loading displacement, the specimen exhibited obvious stiffness degradation. When the load reached 72 mm, the bearing capacity of the specimen decreased significantly, the plastic deformation increased sharply, and the specimen failed.

![Figure 3. JD-1 cell meshing.](image)

![Figure 4. Hysteretic curve.](image)
3.2. Comparison of Destruction Phenomena

Figure 5 shows the final failure mode of the new outer hoop joint under cyclic displacement loading and the final plastic strain cloud diagram of the finite element simulation. Comparative analysis could be seen:

1) The final destruction position was the same. The final penetration cross-section of the specimen in figure 5 (a) and figure 5 (b) was at the junction of the outer hoop steel plate and the concrete beam where the maximum plastic strain was generated. Plastic hinges were formed here and eventually develop into bending ductility failure at the beam end.

2) The distribution of cracks at the left and right beam ends was relatively symmetrical. The plastic strain distribution at the end of the concrete beam in figure 5 (b) was basically symmetrical, indicating that the crack development was also symmetrically distributed, which was basically consistent with the experimental phenomenon.

3) The upper steel column, anchor bolt, screw rod and lower concrete column in the test and finite element simulation were not damaged.

To sum up, the damage phenomenon and final shape of the new type of outer hoop joints were consistent with the finite element calculation results.

3.3. Skeleton Curve Comparison

Take the extreme points on the P-△ hysteresis curve under cyclic loading at all levels to form an envelope to obtain the column top load-displacement skeleton curve. Figure 6 shows the comparison between the experimental and finite element analysis skeleton curves of the JD-1 specimen.

It could be seen that the trends of the two skeleton curves were basically same. The positive skeleton curve was in good agreement, and the error of the positive load characteristic value of the two was within 10%. The test curve showed an obvious "Bauschinger" effect, and there was no obvious decline in the negative direction. The finite element skeleton curve was basically symmetric in positive and negative directions, and the error was within the allowable range.
3.4. Comparison of Stiffness Degradation Curves
Under the action of cyclic reciprocating load, the comparison curve of JD-1 test and finite element stiffness degradation is shown in figure 7, where the abscissa $\Delta$ represents the loading displacement, the ordinate $K_i$ represents the secant stiffness [10], the specific calculation formula is as follows:

$$K_i = \frac{+F_i - |-F_i|}{+X_i - |-X_i|}$$  \hspace{1cm} (1)

where: $+F_i, -F_i$ load values at the $i$-th positive and reverse peak points; $+X_i, -X_i$ displacement values at the $i$-th positive and reverse peak points. It could be seen that the degradation trends of the two curves were basically the same, which be divided into two stages: rapid degradation and slow degradation. The stiffness of the finite element model and the test degraded by 84.05% and 78.90% respectively, the error was within the allowable range, and the stiffness of the two was basically the same in the final failure stage. It showed that the finite element calculation results had certain accuracy and could be used for follow-up research.

3.5. Stress Strain Analysis
Figure 8 shows the Mises stress and plastic strain distribution of concrete, reinforcements, steel, and anchor bolts when the JD-1 specimen reaches its ultimate bearing capacity under reciprocating load. It could be seen that the maximum plastic strain of the concrete exceeded the limit strain value, and the cracks at the edge of the outer hoop steel plate penetrated. The plastic strain of joint domain at the beam-column interface was small under the action of the "hoop". The Mises stress of the beam longitudinal reinforcement continued to increase, and the maximum value reached 562.7 MPa. The maximum Mises stress of the upper steel column was still located at the lower bottom of the steel column near the stiffening ribs, and its maximum value was 300 MPa, reaching a yield strength of 299.55MPa. The maximum stress of screw and anchor parts was located on the upper part of the anchor bolt, and its maximum stress was 123.9 MPa, none of which had reached yield.

As shown in figure 5(b), when the specimen was finally failure, the concrete beam at the edge of the outer hoop steel plate was seriously damaged, the plastic hinge was fully developed, the crack was completely penetrate, and the joint bearing capacity dropped rapidly; the upper and lower longitudinal reinforcements of the concrete beam reached yield, and the maximum stress reached 585.9 MPa; the stress of the steel column was relatively small, and the maximum stress was 230.3 MPa. The anchor bolt stress continued to increase, but it did not reach yield.

It could be seen that the core area of the joint was effectively protected, so that the position of the plastic hinge was moved outside to the edge of the outer hoop steel plate. The upper steel column, screw, anchor bolt and concrete column were well connected, and no obvious damage occurred. The continuity of the force transmission path was guaranteed, which was beneficial to improve the bearing capacity of the joint.
4. Research on the Influence of Axial Compression Ratio

On the basis of the verification of the correctness of the above-mentioned finite element model, the modeling process, geometric material characteristics, loading system and boundary conditions of JD-1 were kept unchanged, and the force characteristics and changing laws of box-shaped column joints were further studied by changing the axial compression ratio of the steel column.

By changing the size of the axial compression ratio at the top of the steel column to simulate the change of the superstructure load in the actual project, and keeping the other parameters of JD-1 unchanged, the 7 different axial compression ratio specimen models shown in table 2 were established.

| Model number | Axial compression ratio | Axial pressure /kN | Column top pressure /MPa |
|--------------|------------------------|--------------------|-------------------------|
| JD-1-1-1     | 0.05                   | 65                 | 4.51                    |
| JD-1-1-2     | 0.10                   | 130                | 9.03                    |
| JD-1         | 0.16                   | 210                | 14.58                   |
| JD-1-1-3     | 0.20                   | 255                | 17.71                   |
| JD-1-1-4     | 0.25                   | 316                | 21.94                   |
| JD-1-1-5     | 0.30                   | 380                | 26.39                   |
| JD-1-1-6     | 0.35                   | 443                | 30.76                   |

4.1. Hysteresis Curve Comparison

Figure 9 shows the hysteresis curves of the other 6 specimens except JD-1 (see figure 4) under the action of low-cycle repeated loads. The comparison showed that their shapes were basically the same and all relatively full parallelograms, which energy dissipation ability was better. At the beginning of loading, each model was in the elastic stage, the hysteresis loop was thin and sharp, and the energy dissipation capacity was not fully reflected. However, the model had a better bearing capacity and greater initial stiffness. As the loading progresses, the model entered the plastic stage. The area of the hysteresis loops was greatly increased, and its energy dissipation capacity was fully expressed. After the 48mm displacement loading level, the bearing capacity of each model began to decrease, the hysteresis curves began to tilt toward the displacement axis, and the stiffness of the model showed obvious degradation. On the whole, changing the axial compression ratio had little effect on the hysteresis curve of the model.

Figure 9. Comparison of different axial compression ratio on hysteretic curve.
4.2. Skeleton Curve Comparison
After sorting out the hysteresis curve data of each specimen, the skeleton curve comparison chart shown in figure 10 is obtained. It could be seen that the slope of the curves was larger at the beginning of loading, the bearing capacity of each model raise faster, and it had good initial stiffness. The curves were almost the same in the elastic stage. It could be seen that the axial compression ratio had little effect on the bearing capacity of the model at the initial stage of loading; after entering the elastoplastic stage, as the axial compression ratio increased, the bearing capacity of the model increased to a certain extent.

![Figure 10. Comparison of different axial compression ratio on skeleton curve.](image1)

![Figure 11. Comparison of different axial compression ratio on stiffness degradation.](image2)

4.3. Stiffness Degradation Comparison
Figure 11 shows the comparison of the stiffness degradation curves of each specimen under low-cycle repeated loads. On the whole, the development trend of the stiffness degradation curve of each model was basically the same. The curve could be divided into two stages: rapid decline and slow decline based on the 24mm loading displacement as the limit. The increase of the axial compression ratio could increase the initial stiffness of the model to a certain extent. After entering the plastic stage, the stiffness degradation curve of each model gradually approached, and the final stiffness was consistent. From the perspective of the entire loading process, the stiffness degradation of each model was similar, and there was no significant difference.

4.4. Engineering Design Recommendations
In summary, when the axial compression ratio was n<0.16, the bearing capacity and stiffness of the joint were reduced, and the stress of the anchor bolt increased sharply; when 0.16<n<0.25, the yield displacement of the joint increased significantly, and the bearing capacity and initial stiffness was slightly increased, but the effect was not obvious; when 0.25<n<0.30, the yield displacement, bearing capacity and initial stiffness of the joint were significantly improved, and the stress distribution at the bottom of the steel column was relatively uniform; when n>0.30, the bearing capacity of joint was still improved, but the full section of the bottom of the steel column yielded, the ductility was significantly reduced, and the stress of the anchor bolt had a tendency to increase, which was not good for the seismic resistance of the structure. As far as the specimens studied in this paper were concerned, when the axial compression ratio was between 0.25 and 0.30, the overall force performance of the joint was better, and its seismic performance could be fully exerted.

5. Conclusions
In this paper, a nonlinear numerical analysis of a new type of outer hoop box-type column joint specimen under low-cycle repeated horizontal loads was carried out, and the following conclusions were drawn. Of course, these conclusions need to be further verified by more experiments and theoretical analysis.
(1) The failure modes of the new outer hoop box-column joints were all concrete beam hinge failures. The hoop effect of the outer hoop steel plate strengthened the restraint on the core area of the joint and its surrounding members, causing the plastic hinge position of the concrete beam to move outward. It effectively protected the core area of the joint, restricted the relative rotation of the beam and column, more effectively controlled the development of cracks, delayed structural damage, and was conducive to improving the bearing capacity of the joint.

(2) Appropriately increasing the axial compression ratio could improve the bearing capacity, initial stiffness and yield displacement of the new joints to a certain extent. When the axial compression ratio was too large (n> 0.30), the ductility of the joints would be significantly reduced and the anchor bolt part stress would increase. The trend was not good for the seismic resistance of the structure. As far as the specimens studied in this paper were concerned, when the axial compression ratio was between 0.25 and 0.30, the overall force performance of the joint was better, and its seismic performance could be fully exerted.

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