Research on Restoring Force Model of Prefabricated Concrete Beam-column Joint

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Abstract. Starting from the research of fabricated concrete frame structure system, the bolt-end plate connection applied in the steel structure and the combined structure is extended into the reinforced concrete structure to form a frame structure with a high-strength bolt-end plate connection. The quasi-static test was carried out. The test results show that the nodes exhibit good ductility and energy dissipation. In order to further explore the seismic performance of this type of structure, according to the experimental fitting method and the “fixed point pointing” law, on the basis of the skeleton curve’s dimensionless treatment, the resilience model of this kind of nodes is established, and compared with the experimental results, the two agree well, which can be provides a certain reference for elasto-plastic seismic response analysis of this type of structure.

1. Introduction
At present, as a traditional and extensive mode of construction, the cast-in-situ concrete structure has many disadvantages. For example, the construction period is long, the working procedure is various, the site management is in a mess, and there are a lot of potential safety hazards. As a corresponding intensive building mode, fabricated building can be assembled into a whole building by prefabricating part or all of the components of the building in the factory, then transporting them to the construction site, and finally using reliable connections to combine the components. This shows the advantages of fabricated building of good quality, energy saving and environmental protection, shortening of the construction period and resources saving. Therefore, the development of fabricated building is a change of construction mode, a progress of social productivity, and an evolution of social form. Fabricated building is the carrier of transformation and upgrading of China’s traditional construction industry, and also the main development direction of China’s construction industry. Steel structure and concrete structure both occupy a certain market share in fabricated building. Although the factory prefabrication efficiency and construction speed of steel structure are far better than concrete structure, concrete structure has the advantages of easy access to raw materials, convenient construction, good durability and stability compared with steel structure, and in China, concrete construction still occupies a dominant position. Fabricated concrete buildings not only inherit the advantages of durability and stability of cast-in-situ concrete buildings, but also save more resources and have better environmental protection compared with traditional cast-in-situ concrete, which is in line with the
current green building development model advocated by China. At present, scholars at home and abroad have made good achievements in the research of fabricated concrete structures [1-6]. In order to further promote the development and application of fabricated concrete structures in China, it is of great significance to carry out the research on fabricated concrete frame system.

2. Basic structure of fabricated beam-column joint
From the existing research results, bolt-end plate connection used in steel structures and composite structures shows better seismic performance, but it has less application in concrete structures. In this paper, bolt-end plate connection is extended to concrete structures. The ordinary steel bars are welded vertically with the end plate by enlarging the pier head, and the prestressing tendons do not pass through the core area of the joint. In addition, steel plate hoop is used to replace stirrups in the core area of joints to avoid the complex phenomenon of steel bars in the core area of joints. Prefabricated concrete beams and columns are connected by eight HTH1080 high-strength screw. There is a gap of 10 mm between the end plate and the column for grouting treatment. The reinforcement of the member is shown in Fig. 1. The steel bar skeleton of the member is shown in Fig. 2.

3. Establishment of restoring force model of fabricated beam-column joints
Because the factors affecting the restoring force characteristics of the core-through high-strength bolt-end plate connection beam-column composite parts are complex, it is difficult to establish the
restoring force model by theoretical method. The hysteretic curve and skeleton curve obtained from
the quasi-static test are summarized and simplified, and the restoring force model of the composite
parts is established. The skeleton curve is processed with dimensionless treatment, the abscissa is
represented by $\Delta/\Delta_y$, and the longitudinal coordinate is represented by $P/P_{\text{max}}$. The results
of dimensionless skeleton curve are shown in Fig. 3.

![Graph showing dimensionless skeleton curve](image)

Figure 3. The dimensionless skeleton curve of the specimen

As can be seen from Fig. 3, the trend of dimensionless skeleton curve is basically the same, and the
characteristic points are basically the same. Therefore, the skeleton curve can adopt the trilinear model
with stiffness degradation. The key points are yield displacement $\Delta_y$, yield load $P_y$, limit
displacement $\Delta_{\text{max}}$, limit load $P_{\text{max}}$, failure displacement $\Delta_u$ and failure load $P_u$. As shown in Fig. 4,
according to linear regression, a unified skeleton curve model can be obtained. The regression
formulas of each segment are shown in Table 1.

| Line segment | Regression equation | Angle with horizontal axis |
|--------------|---------------------|---------------------------|
| OA           | $y = 2.412x$        | 67°                       |
| AB           | $y = 0.486x + 0.514$ | 60°                       |
| BC           | $y = -0.345x + 1.345$ | 58°                      |
| OA’          | $y = 2.259x$        | 66°                       |
| A’B’         | $y = 0.356x - 0.644$ | 20°                       |
| B’C’         | $y = -0.425x - 1.425$ | 23°                      |

3.1. Comparison of skeleton curve

According to the restoring force model, the simulation results are compared with the test results in this
paper. The comparison results are shown in Fig. 5. From Fig. 5, it can be seen that the proposed
trilinear skeleton curve of restoring force is basically consistent with the test curve.
3.2. Hysteretic principle

The restoring force model of fabricated concrete beams and columns under low cyclic repeated loading shows the rule of “fixed point pointing”. The location of the fixed point is approximately the intersection of the positive (reverse) loading curve and the initial curve. The positive (reverse) longitudinal coordinates of the fixed point are 0.5$P_{\text{max}}$. The positive unloading slope is the same as the positive elastic stiffness $K_0^+$ before the member yields, and the reverse unloading slope is the same as the reverse elastic stiffness $K_0^-$ before the member yields. The restoring force model and hysteretic principle are shown in Fig. 6. The mathematical description of the restoring force model is as follows: when loading, the load-displacement curve moves along the skeleton curve OABC, the specimen is in the elastic stage before yielding, and the loading and unloading routes of the specimen are along the OA section (OA’ section). After the specimen yields, the loading path proceeds along the direction of AB (A’B’). The positive unloading route is from 1 to 2, and the unloading stiffness is $K_0^+$. The reverse loading path passes through “reverse fixed point” from 2 to 3, the reverse unloading route from 3 to 4, and the reverse unloading stiffness is $K_0^-$. The positive loading path passes through the “positive fixed point” from 4 to 1. Thereafter, the loading of the specimens continues along the skeleton curve and cycles back and forth according to the above rules until it enters the next stage. From the peak load to the failure (0.85 times the peak load), the loading path is along BC (B’C’). The loading and unloading rules at this stage are similar to those mentioned above.

Figure 5. Comparison of test skeleton curve and simulated skeleton curve.
3.3. Comparison of hysteretic curve comparison

According to the established skeleton curve and hysteretic principle, the hysteretic curves of six core-through high-strength bolt-end plate connection beam-column composite members are compared and analyzed. The results are shown in Fig.7. From the figure, it can be seen that the trend of hysteretic curves calculated by each specimen is basically consistent with the hysteretic curves obtained by the test, which shows that the proposed trilinear restoring force model can better predict the stress and hysteretic performance of this kind of structure.

4. Conclusion

1) According to the quasi-static test results of the fabricated concrete beam-column joints proposed, the skeleton curves and hysteretic curves of four specimens can be obtained, and the skeleton curves and hysteretic curves can be processed with dimensionless treatment. It is
found that the dimensionless skeleton curves conform to the trilinear model law, and the hysteretic curves conform to the “fixed-point pointing regulation”.

2) Based on the experimental fitting method and the “fixed point pointing regulation”, the hysteretic principle of the unified skeleton curve and the restoring force model of the fabricated concrete joint is established. The calculated restoring force model is compared with the experimental hysteretic curve. The results show that the coincidence of the skeleton curve and the hysteretic curve is good. Therefore, the proposed restoring force model can be used as the reference for the elasto-plastic analysis of this kind of frame structure, but this model is only applicable to the design of composite joints with small axial compression and simple “strong column and weak beam”.

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