Research on the restoring force model of an assembled beam-column joint with ring-grooved rivets

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Abstract. To establish the restoring force model of a kind of prefabricated beam-column joints with ring-grooved bolts, the dimensionless skeleton curves and the stiffness degradation law of the joint are obtained by the regression analysis. Therein, the skeleton curves are a trilinear model divided into elastic, reinforcing and degradation stages. The calculated skeleton curves and restoring force model are in good agreement with the experimental skeleton and hysteretic curves. The result shows the restoring model can express the stiffness degradation characteristics of the joint well, as well as provide a theoretical basis for the nonlinear dynamic analysis of structures.

1. Introduction
The mechanical characteristics of beam-column joints have an important influence on the stress state, internal force distribution and deformation characteristics of the steel frame[1]. In the design phase, beam-column joints are usually simplified as completely rigid joints or ideal hinged joints. However, most of the beam-column joints used in practical engineering are semi-rigid joints with mechanical behaviours between the fully-rigid joints and the hinged joints. When the joints are calculated according to rigid or hinged assumptions, the results of internal force analysis of the steel frame will be greatly deviated[2]. Therefore, an appropriate restoring force model must be adopted to express the strength, stiffness, ductility, energy dissipation capacity and other characteristics of the beam-column joints when conducting the nonlinear dynamic analysis of the structure of the frame with semi-rigid joints[3].

Literature [4] proposed a new type of fabricated square steel tubular column-H-shaped beam joints for steel structures, and carried out relevant tests and theoretical studies on its seismic performance. In order to guide its further application in practical engineering design work, through the regression analysis of experimental data, the dimensionless skeleton curve and the stiffness degradation rule of the joint specimens were obtained to calculate the skeleton curves, restoring force model.
2. General test situation
The joint is composed of a square steel tube column, a H-shaped steel beam, a channel steel, a stepped angle steel, a T-shaped backing plate, high-strength bolts and ring-groove rivets. The angle steel is welded in the four corners of the square steel tube column and forms four grooves where the welded combination component of the H-shaped steel beam, channel steel, and T-shaped backing plate is inserted into, and the flanges of the channel steel and angle steel are fixed by high-strength bolt, while the ring-groove rivets cross through the channel steel, T-shaped backing plate, and column web on the one side to tighten them by exerting pretension. Related seismic performance tests were carried out on two 1:1 full-size joint specimens, JD1 and JD2. The only difference between the specimens is that the core of JD2’s column has a diaphragm welded inside, and the other geometric dimensions are the same: the height of the square steel tube column is 3.6m and the section is 350mm×16mm, the length of the H-shaped steel beam is 2.8m and the cross section is 500mm×200mm×10mm×16mm. The structure and detailed dimensions of the joint are shown in figure 1 and figure 2, respectively.

In the test, the loading process was divided into two stages: load control and displacement control. According to the finite element calculation results before the test, the testing load at the load control stage was 50kN per level and each level of load in a loading cycle exerted once; while at the displacement control stage, 0.5 time of the yield displacement for twice at per loading level was applied to control the loading process after the joint yielding until the joint specimens reached to the failure conditions. The loading setup and scheme are respectively shown in figure 3 and figure 4.

3. Establishment of restoring force model
The restoring force model is a practical mathematical model based on numerous relationship curves between the restoring force and deformation obtained from tests with appropriate simplification[5]. It is necessary to simplify the hysteretic curves of joints to realize the programmed application of semi-rigid joints in the time-history analysis of structures. Restoring force models are generally divided into two types: curve and fold types[6]. The curvilinear restoring force models can reflect the continuous change of stiffness, and the calculation results are more consistent with the fact. However, their formulas are more complex and the numerical calculation is difficult, so there are many inconveniently for the curvilinear restoring force models in the elastic-plastic analysis. Relatively, although the folding linear restoring force models are not accurate response of the structure of the mechanical properties, but the choices of algorithm and formula are simple and practical. Therefore, linear restoring force models are always chosen for analysis, particularly the two-line, three-line and sliding models[7].
Because the bearing capacity and displacement of test specimens are different, it is difficult to express their seismic responses with a unified formula. The $P/P_u$-$Δ/Δ_u$ relationship curves were obtained through the dimensionless processing on the pseudo static test data of test specimens, as shown in figure 5. $±P_u$ and $±Δ_u$ are respectively the peak force in the forward and backward directions and the corresponding displacements. It can be seen that the shapes of dimensionless skeleton curves are obviously in good agreement with the three-line restoring force model with the yield point, ultimate load point and failure point as the control points, as shown in figure 6. Points A and A’, B and B’, C and C’ are respectively the yield points, the ultimate load points and the failure points in the forward and backward directions. Through the linear regression analysis of dimensionless data points between the control points, various regression equations of the three-line restoring force model in the two directions at the elastic stage, yield stage and failure stage were fitted respectively, as listed in table 1.

![Figure 5. Dimensionless skeleton curves](image1)

![Figure 6. 3-line restoring force model](image2)

| Line | Regression equation |
|------|---------------------|
| OA   | $P/P_u^*=1.7264Δ/Δ_u^*$ |
| AB   | $P/P_u^*=0.1996Δ/Δ_u^*+0.8106$ |
| BC   | $P/P_u^*=-0.175Δ/Δ_u^*+1.1502$ |
| OA’  | $P/P_u=1.7596Δ/Δ_u$ |
| A’B’ | $P/P_u=0.1281Δ/Δ_u^*-0.8782$ |
| B’C’ | $P/P_u=-0.2048Δ/Δ_u^*-1.2084$ |

The comparison between the experimental skeleton curves and the calculated skeleton curves are shown in figure 7. It can be seen that the experimental and calculated curves are consistent basically, and only small deviation exists in the local parts of the skeleton curves.
According to literature [4], this joint has stable stiffness degradation performance. The load-displacement data of each specimen under all levels of load amplitude were analysed by linear regression method to obtain the calculated stiffness in multiple load cycles, and then the calculated stiffness was analysed by regression to summarize the stiffness degradation law of the joint. Considering the influence of residual deformation, linear regression analysis was conducted on the data points between the loading start point and end point to fit the slopes of calculated skeleton curves as the loading stiffnesses of specimens [8]. The fitted stiffness $K$ was processed by dividing the initial stiffness $K_0$, and the dimensionless $K/K_0$ was depicted in a scatter figure with $\Delta/\Delta_u$ for nonlinear regression analysis to obtain the regression equations of joint stiffness degradation law shown as equation (1) to (4), in which $K_0^+$ and $K_0^-$ are respectively the initial stiffness in the forward and backward directions, and $K_1$, $K_2$, $K_3$, and $K_4$ are the forward loading stiffness, the forward unloading stiffness, the backward loading stiffness and the backward unloading stiffness, respectively.

$$\frac{K_1}{K_0^+} = \exp \left[ -0.22321 + \frac{0.1069\Delta}{\Delta_u} - 0.98527 \left( \frac{\Delta}{\Delta_u} \right)^2 \right]$$  

$$\frac{K_2}{K_0^+} = \exp \left[ 0.02991 - \frac{0.39926\Delta}{\Delta_u} + 0.17853 \left( \frac{\Delta}{\Delta_u} \right)^2 \right]$$  

$$\frac{K_3}{K_0^-} = \exp \left[ -0.0545 + \frac{0.32477\Delta}{\Delta_u} - 1.51901 \left( \frac{\Delta}{\Delta_u} \right)^2 \right]$$  

$$\frac{K_4}{K_0^-} = \exp \left[ 0.01866 - \frac{0.2975\Delta}{\Delta_u} + 0.08742 \left( \frac{\Delta}{\Delta_u} \right)^2 \right]$$

Accordingly, the restoring force model of the joint can be established as figure 8, and the hysteretic law is as following: at the elastic stage, the hysteretic curve goes along the path of $a\rightarrow b \rightarrow c \rightarrow d \rightarrow e$ without the consideration of stiffness degradation; when it reaches to the yield point, the hysteretic curve goes along the path of $f\rightarrow g \rightarrow h \rightarrow i \rightarrow j$ circularly; while beyond the ultimate point, the curve goes along the path of $k\rightarrow l \rightarrow m \rightarrow n \rightarrow o$. The comparison between the calculated restoring force model and the experimental hysteretic curves is shown in figure 9, and the curves are in good agreements. The sources of difference come can be contributed to the sliding of test joint specimens and the linear simplification of the restoring force model.
4. Conclusion
In this paper, the three-line fold skeleton curve model of a beam-column joint was established through the analysis of the pseudo-static test results, and it is in good agreements with the experimental skeleton curves. And by regression analysis, the stiffness degradation equations for the hysteretic curves at the loading and unloading stages were obtained. Based on the skeleton curve model and the stiffness degradation law, the calculated hysteretic curve model was fitted and also in good agreements with the experimental results, reflecting the hysteretic characteristics of joints and providing a certain reference for the design of the joint.

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