ISSN: 1813-4890

Analysis of mechanical properties of semi-rigid joints of new prefabricated beams and columns under low-cycle repeated loads

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Abstract

The influence of different bolt strengths on the mechanical properties of the semi-rigid joints of the new prefabricated beams and columns and the law of change were studied. The finite element software ABAQUS was used to establish a numerical model of the edge joints, and the mechanical properties of different bolt strengths were compared. Results With the increase of bolt strength, the bearing capacity of the specimen increased, and the pinch effect of the hysteresis curve did not change much, indicating that the seismic capacity of the specimen was improved. As the bolt strength increases, the ductility of the joints increases, and the initial stiffness varies between the individual bolt strengths, but the final stiffness is all about the same. The semi-rigid joints of the new prefabricated concrete beams and columns have good seismic capacity, and by comparing the influence of each mechanical property and the actual situation, the high-strength bolts of 8.8 grade are still used in the actual project.

Keywords

Bolt strength; semi-rigid nodes; finite element analysis; Mechanical properties.

1. Introduction

Compared with cast-in-place concrete buildings, prefabricated concrete buildings have a shorter construction period, are more convenient to install, and do not require a lot of manpower, and are widely used in the construction field in today's society [1-4]. However, the quality of prefabricated buildings depends on the connection form of beam-column joints, and the connection mode of semi-rigid joints is one of the connection methods [5-8].

Yuan Yan [9] studied the seismic performance of prefabricated structures by connecting beams and columns with high-strength bolts. The node was studied by using finite elements. Through the research, it can be found that the bearing capacity of the joint has been improved, and the hysteretic curve is relatively full, but the bolt strength should not be too high. Ye Yu [10] proposed a way to connect beams and columns with bolts and angle steel, and designed a semi-rigid joint in this way. Through the test and numerical simulation of the bolts of two strengths, it is concluded that the ultimate bearing capacity of the joint is higher than that of the lower strength, and when the joint bears the force, its stiffness degradation rate is also slower than that of the lower strength, indicating that it has good deformation capacity and is simpler to operate than the rigid joint. Cai Yong et al. [11] welded channel steel to connect the components through bolts. Through experiments and finite element simulations, the performance of the nodes was studied. It can be seen from the test results that the energy dissipation capacity and deformation capacity of the semi-rigid joint have been improved, and the loading along the long axis has almost no effect on the ultimate bearing capacity of the new semi-rigid steel joint, but has a certain impact on the initial stiffness, ductility, stiffness degradation and energy dissipation

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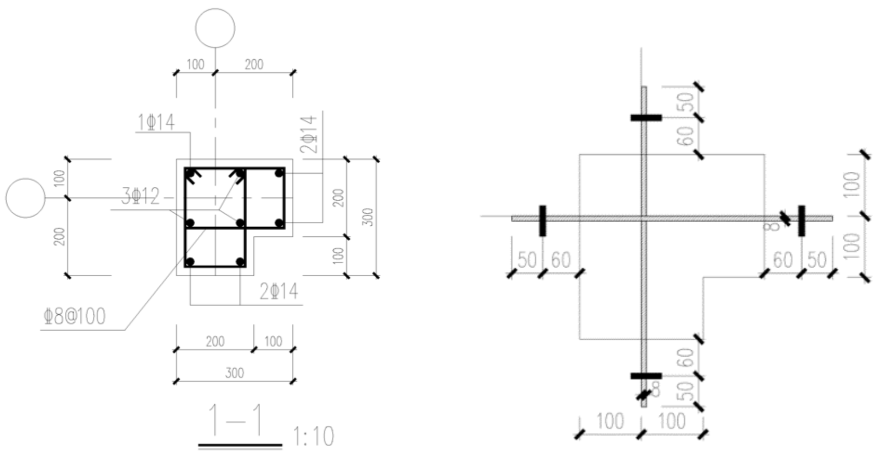
capacity of the joint. Zhan Xin-Xin et al. [12] carried out six quasi-static tests on the bolted connection between a square hollow steel (HSS) column and a double cover plate of an H-section beam. The failure modes, load-displacement hysteresis curves and skeleton curves, as well as the energy dissipation capacity, stiffness and strength of the joints are obtained. The results show that the joint has good rotational capacity, energy dissipation capacity and reasonable strength and stiffness. Later, the finite element model was established and verified by comparing the finite element analysis with the test results, and when the interstory displacement reached 0.06, the tensile force of the beam flange bolt dropped to 60 ~ 70 % of the original pretension force, indicating that the force of the bolt was smaller than the original one, and the structure might be dangerous.

The above literature has carried out a series of studies on the mechanical properties of the semi-rigid joints of bolted beams and columns, but the influence of bolt strength on the mechanical properties of the semi-rigid joints of beams and columns has not been given. In order to study this influencing factor, a new type of connection method of semi-rigid joints of prefabricated concrete beams and columns is proposed, which is experimentally analyzed by the finite element software ABAQUS [13-15]. The test results are obtained by studying the mechanical properties of the semi-rigid joints of the new prefabricated beams and columns with different bolt strengths. The results show that when the semi-rigid joints of the new prefabricated concrete beams and columns are used with 8.8 grade high-strength bolts, they are better than ordinary bolts in terms of seismic performance and plastic ability.

2. Finite element model

2.1. Geometry

The concrete beam column of the side node and the cast-in-place concrete of the middle connecting part adopt the strength of C30, the cross-sectional width × height of the beam is 200mm×350mm, and the cross-sectional width and ×height of the column are 300mm×300mm. The steel bar is HRB400, the channel steel is Q345 grade steel, and the web thickness of the channel steel is 7mm. The bolt strength of the edge joint member is 4.6 grade, 5.6 grade ordinary bolt, and 8.8 grade high-strength bolt, the bolt diameter is 16mm, and the preload is applied to the bolt, and the preload is unified to 10kN. In order to better install the bolts, the bolt hole with a diameter of 17.5mm is reserved on the channel steel, and the specific reinforcement diagram is shown in Figure 1.



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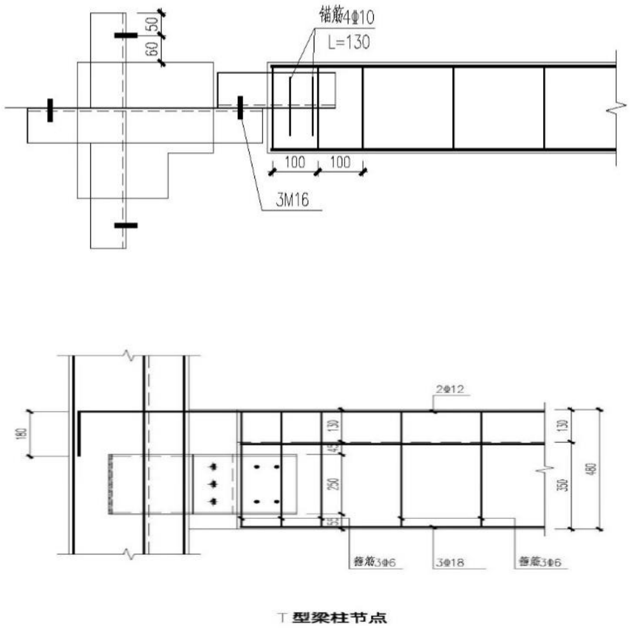


Fig.1 Reinforcement diagram

2.2. Material constitutive relations

2.2.1. Constitutive relationship of concrete

The constitutive model used in this paper is the plastic damage model of concrete, and the stress-strain relationship corresponding to the uniaxial compression-tension of concrete can be obtained through the formula of Appendix C in the Code for the Design of Concrete Structures (GB50010-2010), as shown in Figure 2 is the stress-strain relationship diagram corresponding to the uniaxial compression-tension of concrete.

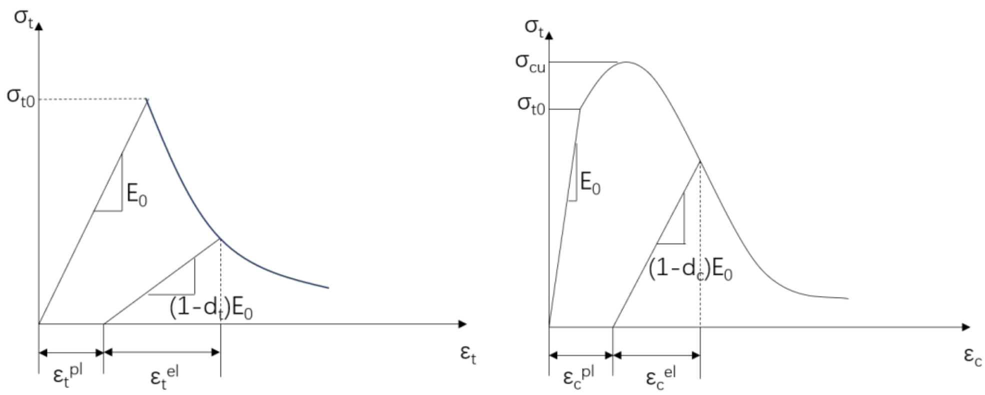


Fig.2 Schematic diagram of concrete compression-pull relationship

Among them, E represents the elastic modulus of concrete after damage, d is the damage factor of concrete, E0 represents the elastic modulus of concrete in the initial stage, and dc and dt correspond to the unloading damage values of concrete under compression and tension, respectively [16-17].

The stress-strain relationship corresponding to the uniaxial compression and tension of concrete materials is shown below.

Expression for uniaxial tension of concrete:

$\sigma=(1-d_t)E_{c\varepsilon}$

当$x\leq1$时，$d_c=1-\rho_t(1.2-0.2x^5)$

当x＞1时， $d_c=\frac{1-\rho c}{\alpha t(x-1)1.7+x}$

$\rho_t=\frac{f_{t,r}}{E_c\varepsilon_{t,r}}$

$x=\frac{\varepsilon}{\varepsilon_{t,r}}$

Expression for uniaxial compression of concrete:

$\sigma=(1-d_c)E_{c\varepsilon}$

当x≤1时， $d_c=\frac{1-n\rho_c}{n-1+x^n}$

当x＞1时， $d_c=\frac{1-\rho_c}{x+(x-1)^2\alpha_c}$

$\rho_c=\frac{f_{c,r}}{E_c\varepsilon_{c,r}}$

$n=\frac{E_c\varepsilon_{c,r}}{E_c\varepsilon_{c,r}-f_{c,r}}$

$x=\frac{\varepsilon}{\varepsilon_{c,r}}$

where αc and αt are used——The parameter value of the descending section of the stress-strain curve of concrete under uniaxial compression and tension shall be taken according to the parameters of the specification table;

$f_{c,r}$, $f_{t,r}$——The representative values of uniaxial compressive and tensile strength of concrete are determined separately according to the actual material test results.

$\varepsilon_{c,r}$, $\varepsilon_{t,r}$——The peak strain of concrete corresponding to the representative values of compressive and tensile strength shall be taken according to the parameters of the specification table;

d_c, d_t——Parameters of concrete compression and tensile damage.

2.2.2. Constitutive relations of steel

According to the Mises yield criterion, the constitutive relationship of the steel is tested by the three-fold line model, and the constitutive relationship between the steel plate and the bolt is shown in Figure 3 [18-19].

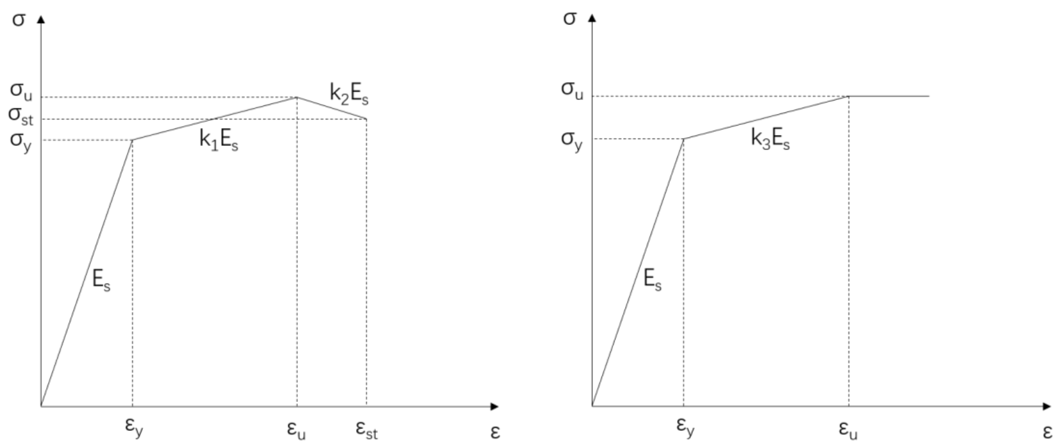


Fig.3 Constitutive model curves of steel and bolts

The constitutive relationship between steel and bolt is as follows.

Constitutive relation of steel:

ISSN: 1813-4890

$$\sigma=\begin{cases} E_s\varepsilon & \varepsilon\le\varepsilon_y \\ \sigma_y+k_1E_s(\varepsilon-\varepsilon_y) & \varepsilon_y<\varepsilon\le\varepsilon_u \\ \sigma_u+k_2E_s(\varepsilon-\varepsilon_u) & \varepsilon>\varepsilon_u \end{cases}$$

The constitutive relation of the bolt:

$$\sigma=\begin{cases} E_s\varepsilon & \varepsilon\le\varepsilon_y \\ \sigma_y+k_3E_s(\varepsilon-\varepsilon_y) & \varepsilon_y<\varepsilon\le\varepsilon_u \\ \sigma_u & \varepsilon>\varepsilon_u \end{cases}$$

thereinto,k1=0.006，k2=0.001，k3=0.006

2.3. Cell Types and Meshing

In order to obtain more accurate results, C3D8R solid elements are used for concrete, channel steel and bolts, and T3D2 in truss elements is used for reinforcement. Since this truss element is in the form of beam by default in the model, it needs to be changed to the form of truss in the software [20-21]. In this paper, based on the principle of optimized meshing, both ends of the column and the non-end part of the beam are sweptly meshed, and the bolts, steel plates and remaining concrete parts are divided by hexahedral free meshing, as shown in Figure 4 below.

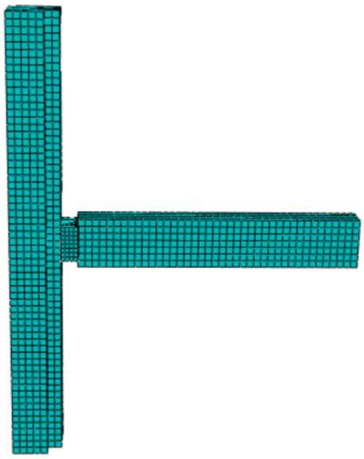


Fig.4 Meshing diagram

2.4. Boundary Conditions and Loads

The displacement of the column base of the finite element model is fully constrained, that is, the boundary condition is set to U1=U2=U3=UR1=UR2=UR3; The remote displacement of the column top of the finite element model constrains the three-way translational degrees of freedom, that is, the boundary condition is set to U1=U2=U3=0. For the boundary conditions of the finite element model beam, a reference point RP1 is established at the beam end, a low-cycle reciprocating load in the vertical direction is applied to the coupling point at the beam end, and then the displacement is constrained, that is, the boundary condition is set to U1=U3=0, U2=5, the loading displacement curve of the beam-column joint is shown in Figure 5, and a preload of 10kN is applied to each bolt. The default convergence criterion is optimized to improve efficiency and calculation accuracy while ensuring the results.

ISSN: 1813-4890

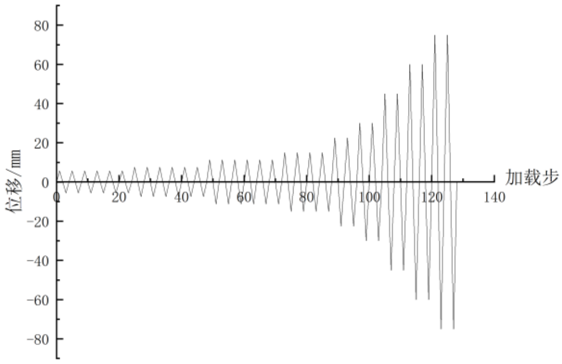


Fig.5 Loading regime

3. Finite element simulation results

3.1. Node Failure Patterns

Since the plastic damage model is used for the constitutive model of concrete in FEA ABAQUS, the tensile damage and compressive damage of the prefabricated semi-rigid edge joint under low-cycle reciprocating load can be analyzed [22], and the tensile damage and compressive damage of concrete can be shown in Figure 6 below.

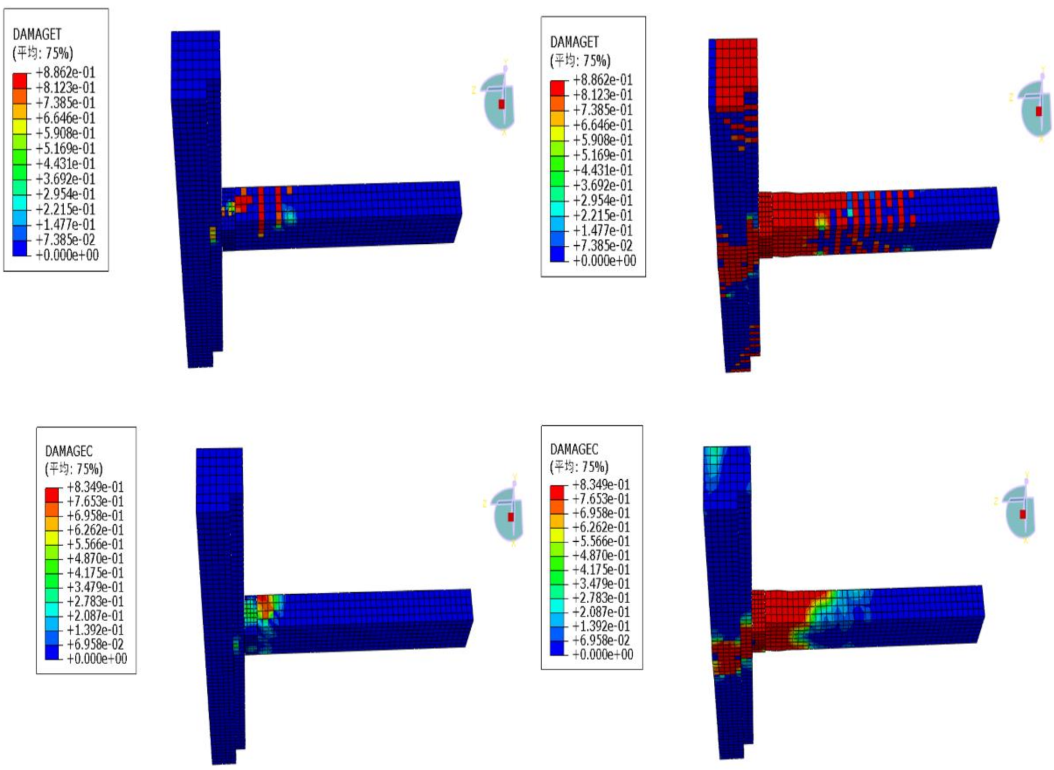


Fig.6 Concrete plastic damage model

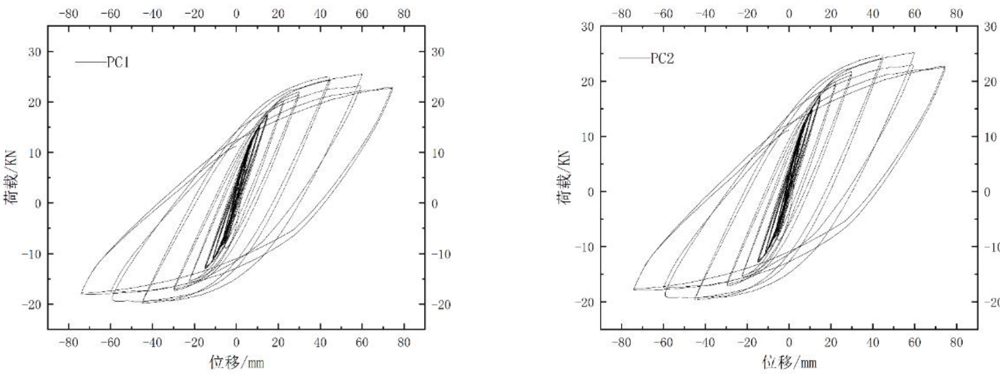
In ABAQUS software, since the plastic damage model is used for concrete, the failure of the concrete in the component can be reflected through the tensile damage contour (DAMAGET) and compression damage contour (DAMAGEC) of the concrete in ABAQUS post-processing. The larger the values of DAMAGET and DAMAGEC, the greater the degree of concrete failure at this time.

By observing the tension and compression states of the joint, it can be concluded that the specimen has been completely destroyed. From the initial stage of loading, the joint initially maintained an elastic state, and the concrete damage was not large, but with the continuous increase of load, the flange of the prefabricated beam-column joint first began to failThe plastic damage to the nodes slowly began to become severe. The damage of the specimen starts at the flange of the beam-column joint, then cracks begin to appear in the part of the beam connection and continue to extend towards the other end of the beam, and finally the concrete beam outside the core area of the beam-column node fails. This kind of failure is mainly concentrated in the external concrete at the joint of the joint, which plays a good role in protecting the core area of the joint, which conforms to the design method of "strong column and weak beam" and "strong node weak member", which shows that the ABAQUS software has a good simulation and analysis of the semi-rigid joint of the new prefabricated concrete beam and column.

3.2. Hysteresis curves

By observing the hysteresis curve, we can see the seismic performance of the joint in the whole process, and the hysteretic curve of the edge node with different bolt strengths is shown in Figure 7 below.

Through the observation of Figure 7, it can be seen that the hysteresis curve of the joint is relatively full, and the concrete is in the elastic stage in the early stage of load loading, and the concrete is not cracked. When the displacement is reached, the concrete begins to crack due to tension, and the specimen begins to undergo residual deformation. When the load continues to increase, the concrete specimen changes from the elastic stage to the yield stage, and the area enclosed by the hysteretic loop gradually increases, but the slope of the hysteretic loop begins to decrease, indicating that the stiffness of the joint is also decreasing. When the load on the concrete specimen continues to increase, the specimen reaches the ultimate bearing capacity, the hysteresis curve of the specimen changes from the rising stage to the descending stage, and the stiffness of the node gradually degrades. The difference in the yield displacement of the specimen of the edge node is not large, the area of the hysteretic loop surrounded by the hysteretic curve continues to increase, the residual deformation continues to increase, and the energy dissipation of the node also continues to increase. The pinching effect caused by the hysteresis curve of the specimen is also small, which indicates that the energy dissipation capacity of the node is better. At the same time, with the increase of bolt strength, the bearing capacity of the node also increases accordingly.



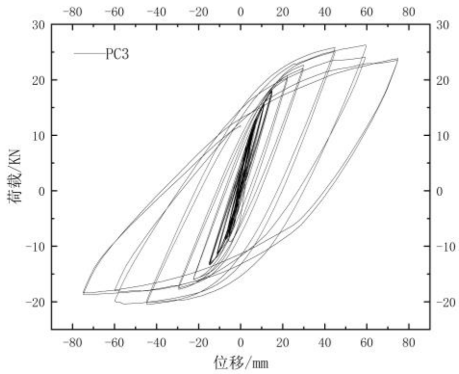


Fig.7 Hysteresis curves of different bolt strengths

3.3. Skeleton curves

The skeleton curve is the trajectory curve about the maximum peak of the horizontal force obtained according to the hysteresis curve of each cyclic load, and the situation of each node can be obtained from the skeleton curve, and the skeleton curve of each node is shown in Figure 8 below.

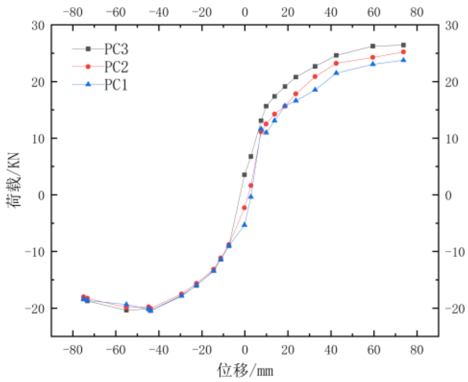


Fig.8 Skeleton curves of different bolt strengths

It can be seen from Fig. 8 that the shape of the skeleton curve of the edge node is roughly S-shaped, in the early stage of load loading, because the concrete at this time has not been destroyed, the specimen is still in the elastic stage, so the bearing capacity of the node maintains a linear growth with the loading of the load, the energy consumption of the specimen is small, with the continuous increase of load, the concrete begins to crack, and the curve begins to grow slowly, indicating that the growth of the bearing capacity of the node at this time becomes slower, and the stiffness of the node begins to decrease; With the increasing load, the specimen also changes from the elastic stage to the yield stage, the growth of the curve becomes more and more gentle, the bearing capacity of the node increases more slowly, and the stiffness degrades obviously. When the bearing capacity reaches the ultimate bearing capacity, the curve begins to enter the descending section, indicating that the bearing capacity of the node gradually decreases from the maximum value. The yield displacement of the joint when it reaches the ultimate bearing capacity reflects the quality of the bearing capacity of the joint, and the larger the yield displacement, the better the overall bearing capacity. When the bolt strength is 4.6, the ultimate bearing capacity of the joint is the smallest, and with the gradual increase of the bolt strength, the ultimate bearing capacity of the joint also increases. The ultimate bearing capacity of the bolt strength of 5.6 is 13.6% higher than that of the bolt strength of 4.6, and the ultimate bearing capacity of the bolt is 6.1% higher than that of the bolt strength of 5.6, which indicates that the overall bearing capacity of the specimen can be improved with the improvement of the bolt strength. Since the high-strength bolt of grade 8.8 has the largest bearing capacity and the lifting range is also greater, the high-strength bolt of grade 8.8 is more in line with the design requirements.

3.4. Ductility Analysis

The structural failure of buildings is generally divided into ductile failure and brittle failure, and brittle failure should be avoided as much as possible in engineering. Ductility is generally expressed by ductility coefficients, which are calculated according to the yield displacement and ultimate displacement of the joint, and Table 1 lists the yield displacement, ultimate displacement and ductility coefficient of the joint under different bolt strengths.

Table1 Ductility coefficients of different bolt strengths

Specimens	Yield displacement /mm	Limit displacement /mm	ductility
1	24.88	70.85	2.85
2	23.11	68.57	2.97
3	19.80	66.28	3.35

It can be seen from Table 1 that the ductility of the concrete specimens of the edge joints is greater than 2 under different bolt strengths, indicating that the plasticity of the new prefabricated concrete beam-column joints is relatively good. When the bolt strength increases, the yield displacement, ultimate displacement and ductility coefficient of the specimen change. For the specimen, the ductility coefficient of a bolt strength of 8.8 is 6% higher than that of a bolt strength of 5.6. The bolt strength is 5.6, and the ductility coefficient of the high-strength bolt is 2.7% higher than that of the bolt strength 4.6.

3.5. Stiffness degradation

The stiffness degradation can reflect the damage of the structure when it is subjected to loads, and the secant stiffness can be used to represent the stiffness degradation of the specimen, as shown in Figure 9.

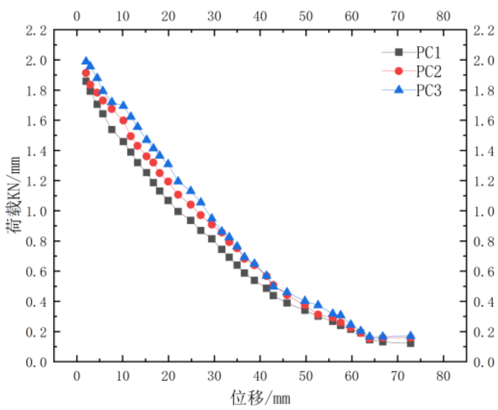


Fig.9 Degradation of different bolt strength stiffness

From the stiffness degradation curve of the specimen, it can be obtained:

1) When the load is loaded in the early stage, the slope of the stiffness degradation curve is larger, indicating that their descent rate is faster in the early stage. With the gradual increase of the load, the displacement is also increasing, the slope of the curve of stiffness degradation begins to slowly decrease, and the rate of decline begins to slow down, which indicates that the members work in harmony with each other when they are under load. As can be seen from the

ISSN: 1813-4890

figure, when the bolt strength is 4.6, the initial stiffness of the specimen is 1.88KN/mm. When the bolt strength is 5.6, the initial stiffness of the specimen is 1.93KN/mm, which is 2.7% higher than that of the 4.6 bolt. When the bolt strength is 8.8 grade high-strength bolt, the initial stiffness of the specimen is 2.02KN/mm, which is 4.7% higher than that of the 5.6 bolt. With the increasing load of different bolt strengths, the subsequent stiffness is always approximately the same.

2) With the increase of bolt strength, it can be seen that the stiffness of the specimen is generally higher than that of the previous bolt, and the stiffness increased by the bolt strength grade from 4.6 to 5.6 is slightly smaller than that of the high-strength bolt from 5.6 to 8.8, indicating that the improvement of bolt strength can improve the overall stiffness of the specimen.

4. Conclusion

1) The hysteretic curve shape of the new prefabricated concrete semi-rigid joint under low-cycle reciprocating load is relatively full, and the curve shows a more obvious pinching effect, and when the bolt strength increases, the pinching effect of the curve is improved, and the bearing capacity is also increased accordingly. The skeleton curve of the specimen decreases quickly and the slope is large in the early stage of loading, and gradually decreases as the load continues to increase. When the bolt strength increases, the ultimate bearing capacity of the specimen also increases. When the bolt strength increases, the degraded stiffness of the specimen has a greater initial stiffness, and the curve of the degraded stiffness gradually flattens out as the load gradually increases, indicating that the specimen is working normally.

2) The ductility of the joints with different bolt strengths is greater than 2, which meets the requirements of the project for beam-column joints. As the strength of the bolt increases, the ductility of the joint gradually increases, indicating that the stiffness of the joint increases, but the ductility of the node increases.

3) With the improvement of bolt strength, the seismic capacity of the semi-rigid joints of the new prefabricated concrete beams and columns is affected, and the higher the bolt strength, the better the energy dissipation capacity of the joint, and the safer the components.

4) Based on the comprehensive analysis of the influence of bolt strength on the mechanical properties of the joint and the actual cost, it is more appropriate to use 8.8 grade high-strength bolts.

Acknowledgements

Natural Science Foundation.

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