Quasi-Static Test Study on Three-storey Single-span Fabricated Prestressed Concrete Frame Joints

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Abstract. Based on the quasi-static shock test of a three-storey single-span fabricated prestressed concrete frame, the crack and damage of each node when the test frame is in the ultimate failure state are understood. The crack resistance of each node is calculated and analyzed. The deformation characteristics of the core region of the node are discussed according to the load of displacement and shear angle hysteretic curve, and the nonlinear simulation is carried out with the finite element software ANSYS. The results show that the failure of the fabricated prestressed concrete frame occurs at the end of the beam, while the core area of the joint is not damaged under the condition of two-way stress, which has strong crack resistance and deformation resistance and meets the seismic design requirements of "strong joints and weak components".

1. Introduction
During the construction of the concrete project on site, the construction process such as formwork support, pouring, vibration and maintenance will take up a long construction period, and due to the comprehensive influence of various complex factors such as site environment, personnel and machinery, the construction quality can hardly be guaranteed, and it may cause material waste and environmental damage. The required components are produced in advance in the factory and then assembled on site, which can not only greatly shorten the construction progress, but also ensure high engineering quality of the prefabricated components, and the accuracy of the prefabricated components can also be reduced from centimeter-level to millimeter-level [1]. Factory production and assembly construction are the core production modes of building industrialization [2]. Prefabricated concrete structure is a kind of concrete structure that prefabricate components in the factory first and then assemble and connect the components in the site, which conforms to the characteristics of building industrialization and is the demand of the times for the development of the construction industry [3]. However, the current fabricated concrete structures often lack reliable means of connection at beam-column joints, making it difficult to resist repeated impact of seismic loads and fail to meet the design requirements of "strong joints and weak components" in seismic codes, thereby limiting their application in seismic areas [4]. Thus, the connection problem of beam-column joints restricts the development of fabricated concrete structures and it needs to be solved urgently. Prefabricated prestressed concrete structure is to assemble beam-column members on site with prestress to form the whole structure, which can effectively strengthen the connection of beam-column joint core area. In this paper, a three-storey single-span fabricated prestressed concrete frame is tested
under quasi-static loading, and the stress and deformation behavior of the frame joints are analyzed and studied.

2. Overview of the Test

This test frame is a plane three-storey single-span fabricated prestressed concrete frame. First, the factory prefabricates beam-column components, and then the fabrication is conducted in the laboratory. The test structure belongs to a post-tensioned bonded prestressed concrete frame, and the specific fabrication process is as follows: Lifting beam-column members in place → Traverse the prestressed steel hinge beam in the reserved tunnel → Post-tensioned prestressed tendons → Epoxy resin caulking → Duct grouting [5]. While making the test structure, the concrete of the same batch of materials is made into standard test blocks, and the performance of the test blocks is tested with a universal testing machine to obtain the cube compressive strength standard value, the axial compressive strength standard value, the axial compressive strength design value and the elasticity modulus, so as to determine the measured values of various mechanical properties of the test frame concrete. At the same time, the yield strength, ultimate strength and elasticity modulus $E$ of ordinary steel bars and prestressed steel bars used in the test were also tested. In this test, the scale model, the specific size of the test frame and the reinforcement design are adopted, as shown in figure 1.

![Figure 1. Test frame size and reinforcement design](image1)

![Figure 2. Loading device](image2)

The test loading device consists of a hydraulic servo loader, a hydraulic jack and a reaction frame, etc., as shown in figure 2. The vertical load was applied by a hydraulic jack placed on the top of the column and remained constant throughout the test. The simulation of horizontal seismic force adopts quasi-static mixed control loading mode, i.e. loading is controlled according to the load before the specimen yields, and loading is controlled according to the displacement after the specimen yields [6]. The horizontal displacement control is designed according to the first mode shape with a dynamic degree of freedom of 3: the ratio is 1.0: 0.85: 0.55. To study the strain in the core area of the joint, a bidirectional 90° oblique cross strain pattern is arranged at the beam-column joint and connected with a data acquisition instrument for continuous measurement and automatic recording.

3. Crack and Damage Analysis of Node Core Area

The quasi-static test has a certain intermittent time after each additional level of displacement, hence it is convenient to observe and record the whole process of the stress change of the test frame. This test completely recorded the crack development process in the beam end and column end of each
node core area and its vicinity, and plotted the crack distribution and damage in the node core area under the ultimate bearing capacity of the frame, as shown in figure 3.

![Figure 3. Crack distribution and damage in core area of joint under ultimate bearing capacity](image)

The test shows that when the frame is destroyed, the tensile steel bars at the beam end will yield first, and then the concrete at the edge of the compression zone will be crushed and destroyed, resulting in plastic hinges. Plastic hinge is not exactly the same as ideal hinge, it can not only rotate, but also bear certain bending moment. After the plastic hinge is formed, the beam end has a rotating effect and the internal force is redistributed, which is helpful to the energy consumption of the structure. Through the analysis of crack distribution and damage, it is found that although the concrete at the end of the beam is peeled off and damaged, no crack or damage has been found in the core area of each node. This is because under the combined action of the vertical pressure of the frame column and the horizontal pressure of the frame beam, the restraint performance of the joint is enhanced, the lateral deformation of the concrete is reduced, and the crack resistance of the core area is improved.

4. Analysis of Crack Resistance of Node Core Area

The node is the key part of the frame structure, which is why it is called core area. According to the requirement of "strong joint and strong anchorage" in the conceptual design of seismic structure, the crack state in the core area of the joint must be strictly controlled, hence it is very necessary to analyze the crack resistance of the core area of the joint [7]. Before the concrete cracks, the concrete at the joint position is in an elastic state, which conforms to the hypothesis of Hooke's law of tension and compression. Since there is no crack, the longitudinal reinforcement and stirrup basically do not bear the function of resisting shear force, and the stress of both can be ignored, assuming that the shear force in the core area is completely borne by concrete [8]. According to this assumption, when the main tensile stress in the core area of the joint reaches the ultimate tensile strength of concrete, the joint will be in a critical state of cracking. Intercepting the frame node as an isolator for stress analysis, the formula for calculating the shear force of the node can be obtained from the static equilibrium condition. Since the frame joints in this test are under vertical and horizontal compression, the micro-element analysis is taken out from the core area, and according to the two-way stress intensity theory, the formula for calculating the theoretical value of the shear capacity of concrete in the core area can be derived. By substituting axial compressive stress $\sigma_c$ (8.21 MPa) and horizontal preloading stress $\sigma_p$ (5.62 MPa) into the Formula, the theoretical value $V_{jc}$ of the crack resistance and shear capacity of the joint is 881.5 kN. The results of the comparison between the core shear test values and the theoretical values are shown in Table 1.

| Position of components | Third storey | Second storey | First storey |
|------------------------|--------------|---------------|--------------|
|                        | Node 1       | Node 2        | Node 3       | Node 4       | Node 5       | Node 6       |
|                        | Forward      | Backward      | Forward      | Backward     | Forward      | Backward     |
| $V_{j}$ (kN)           | 138.6        | 118.4         | 429.6        | 387.6        | 607.9        | 552.9        |
| $V_{j}/V_{jc}$ (%)     | 15.72        | 13.39         | 48.51        | 43.62        | 68.34        | 61.95        |

Analysis shows that when the test frame reaches the ultimate bearing capacity state, the shear force value in the core area of the joint changes with the height of the floor. The lower the number of floors,
the greater the shear force, and the largest the bottom shear force, which is in line with the actual structural stress situation. $V_j / V_{jc}$ is less than 1, indicating that in the limit state, the actual shear test values in the core area of the joint are less than the theoretical values, and there is no cracking in the core area of the joint. At this time, the maximum shear test value in the core area of the joint only accounts for 61.95% of the theoretical value, indicating that the core area of the joint has sufficient safety reserve against cracking. This also confirms that the joint core area of the test frame has strong shear resistance under the action of horizontal and vertical two-way pressure and meets the design requirements of "strong joints" in the seismic design code for engineering structures.

5. Deformation Analysis of Node Core Area

After the specimens are loaded, the bending and shearing forces generated by beams and columns are transmitted to the nodes, causing shear deformation in the core area. The shear deformation of the core area will cause the deformation of the beam end and the column end, which will further increase the deformation of the beam and column and adversely affect the structure. Therefore, the deformation analysis of the node core area is of great significance. The alternating change of load cycle makes the concrete gradually enter the stage of plastic deformation, and loops will be formed in the load-displacement pattern. Such loops are called hysteretic curves, also called hysteretic loops [9]. Since the area surrounded by the lower side of the curve and the coordinate axis reflects the simulated seismic energy absorbed by the structure, the area in the middle of the loading and unloading curve is the energy consumed by the structure, which is dissipated through friction and local damage inside the material. The more loading cycles, the greater the deformation and the more obvious the reduction of the bearing capacity. Therefore, hysteretic curves can reflect the characteristics of structural strength, stiffness, ductility and energy dissipation, and are an important method to analyze the seismic performance and failure mechanism of structures [10]. In this test, the shear angle $\gamma$ of the node core is calculated by measuring the concrete strain in the diagonal direction of the node core and using the empirical formula of shear deformation, and the load (displacement)-shear angle hysteretic curve of the core is drawn by origin software. The hysteretic curves of some nodes are shown in figure 4. The load and displacement shown in figure 4 both represent the horizontal direction values applied by the MTS hydraulic servo loader.

As can be seen from figure 4, the shear angle changes of most nodes have common characteristics. In the early stage of loading, the frame concrete is still in a completely elastic state due to the small load, the shear angle is basically unchanged, the figure is oblique and has no hysteretic characteristics. With the progress of loading, the frame enters the plastic deformation stage, the load increase is not large, but the displacement continues to increase, the shear angle increases with the displacement increase, but the increase is slow, and the maximum shear angle value is small, far less than the limit deformation value. Because the shear force in the core area decreases with the increase of the height of the floor, the residual shear angle of the bottom layer is larger and the top layer is smaller after the displacement returns to zero. With the increase of horizontal displacement, the shear angle of some joints gradually decreases, which is due to the loss of the bonding force between the prestressed steel bar and the concrete in the core area and the loss of the ability to transfer shear to the core area. This
may be due to the lack of compactness caused by grout leakage at the joint during the initial grouting of the test and the incomplete combination of prestressed reinforcement and concrete. To sum up, through the analysis of the two hysteretic curves, it is found that the hysteretic curves of shear angles in the core region of most nodes are oblique lines without obvious hysteretic loops, which indicates that the concrete in the core region is always in an elastic state during the loading process and does not produce excessive deformation.

6. ANSYS Nonlinear Analysis
At the end of the test, ANSYS finite element software is used to simulate the complete stress process of the test frame, and non-linear analysis is carried out. Firstly, the constitutive model of concrete, prestressed reinforcement and ordinary reinforcement is established. According to the different material characteristics of concrete and reinforcing steel bar, concrete is defined by SOLID65 unit and reinforcing steel bar is defined by LINK8 unit. The spatial solid model of the test frame is established by using the work plane cutting method, in which the processing of component connection surfaces is completed by using Boolean calculation [11]. Then, the SWEEP or MAP rule is used to accurately mesh the test frame and improve the accuracy of the calculation results [12]. Finally, load calculation was carried out, prestress is applied by cooling method, and external load is simulated by monotonic loading method. The stress distribution of some joint core areas under the ultimate bearing capacity of the test frame is shown in figure 5.

![Figure 5. Simulation of main tensile stress of Nodes](image)

The results of finite element analysis show that the failure of the frame begins at the beam end, while the failure of the core area of the joint does not occur, which is consistent with the test. The main tensile stress of each section appears in diagonal direction, which is consistent with the actual theory. Moreover, when the frame is in the ultimate bearing capacity state, the tensile stress is less than the tensile strength limit of concrete, i.e. $\sigma_{zi} / f < 1$, which shows that there is no crack in the node concrete of the simulated frame, being consistent with the test. Again, it is verified that the core area of the joint under the two-way stress state meets the seismic design requirements of "strong joints". After calculating the main tensile stress test value $\sigma_{zi}$ under the limit state of each node core area, comparing with the stress value $\sigma$ simulated by ANSYS, it is found that the simulation result is close to the actual test result, with the error range within 34.7%. The error is caused by the discreteness of concrete and the approximation of finite element simulation.

7. Conclusion
Through the quasi-static loading seismic test of a three-storey single-span fabricated prestressed concrete frame, the stress and deformation state of the joint core area when the test frame is in the ultimate failure state are analyzed, and the following conclusions are obtained: According to the distribution and damage of cracks in the core area of the joint, there are no cracks in the core area, and
the frame failure occurs at the end of the beam. Through the calculation of crack resistance, it is found that the actual test shear value of each node core area is less than the theoretical value, and the maximum shear test value accounts for only 61.95% of the theoretical value, indicating that the node core area has sufficient crack resistance safety reserves. Through the analysis of the load (displacement)-shear angle hysteretic curves of each node, it is known that the concrete in the core region always remains elastic during the loading process and does not deform excessively. The nonlinear simulation analysis of the test frame was carried out by ANSYS finite element software, and the distribution characteristics of the maximum principal tensile stress in the core area of the frame node obtained by simulation were basically consistent with the test results. The above conclusions confirm the fastening effect of the fabricated prestressed concrete frame joint under the combined action of the axial pressure of the frame column and the horizontal preloading stress. This connection enhances the restraint on the joint concrete, reduce the lateral deformation, improve the crack resistance and deformation resistance of the joint core area, meet the design requirements of "strong joints and weak components" in the seismic design of engineering structures, and improve the overall seismic performance of the structure. This method can be applied to the practical engineering of fabricated concrete to accelerate the industrialization of construction.

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