Parameter Analysis for Seismic Performance of Prestressed Fabricated Frame Joint Based on OpenSees

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Abstract. Aiming at the characteristics of prestressed fabricated frame joints, proposes a finite element modeling method based on OpenSees. Then, verify the correctness of the finite element model combining experiment of prestressed fabricated frame structure. It shows that the proposed joint finite element model can predict the seismic performance of the structure accurately. Detailed parameter analysis is performed to study the general law of seismic performance evolution of joint from five aspects, namely, prestressed tendon area, energy-dissipating tendon area, concrete strength, axial compression ratio, and tensile control stress. Analysis results show that prestressed tendon area, axial compression ratio and tensile control stress should be constrained to some extent, otherwise the performance of joint would deteriorate.

Keywords. OpenSees, prestressed fabricated, frame joints, parameter analysis.

1. Introduction
Prestressed fabricated concrete frame structure is one of the most widely used prefabricated structure systems. Prestressed fabricated frame joints require secondary casting, which has poor integrity. Under the action of earthquake, the joint is easy to destroy before the component, which is difficult to meet the seismic requirements of strong joint and weak component. At present, experimental research is still the main method for studying the seismic performance of fabricated concrete structures, and numerical simulation is relatively lacking. With the development of computer technology and modern numerical methods, parametric analysis of structures, study of damage evolution laws, prediction of structural performance and test results are important development trends. Choek[1] used a plastic hinge model to simulate the deformation of the assembled frame joint at the beam end, and used the IDARC program to analyse the elastic-plastic time history of frame models with different heights. However, the IDARC program has the defects of complex plastic hinge modelling and cannot consider the cracking behaviour of the beam column interface. El-Sheikh [2] used OpenSees to simulate the seismic performance of partially bonded fabricated frame structures. The opening and closing behaviour of the beam-column interface under earthquake was not considered in the study. Youssif [3] used two springs hinged to the rigid contact surface to consider the shear of the joints, the joints and beam-column elements are connected by springs. The influence of cracks at the interface between beams and columns on the mechanical properties of joints was not considered in the study.

This paper proposes a finite element modeling method based on OpenSees for prestressed fabricated beam-column joints [4-10], and combines the experimental model of fabricated frame structure to verify the correctness of the finite element model. Based on the OpenSees finite element
model, parameter analysis was performed on the joints from five aspects: prestressed tendon area, ordinary reinforcement area, concrete strength, axial compression ratio, and tensile control stress. The general law of seismic performance evolution of fabricated beam-column joints was studied.

2. Simulation of Two-stories Two-span Prestressed Fabricated Frame

2.1. Finite Element Model
The joint finite element model established is shown in figure 1. Nonlinear Beamcolumn element based on fiber cross-section is established between node 1 to 2 and node 3 to 4 to simulate prefabricated columns. Between the node 5 to 6, node 6 to 7, node7 to 8, node 11 to 12, node 12 to 13 and node 13 to 14, Nonlinear Beamcolumn element is established to simulate the prefabricated beam. Concrete 02 material is adopted in both prefabricated beams and columns. Nonlinear Beamcolumn element using Concrete01 material is established between node 8 to 9 and node 10 to 11 to simulate the mortar layer of the joint, considering the mortar cannot stand tension when crack. The prestressed tendons are simulated by truss elements that only bear axial force, and the truss elements share nodes with the beam elements at ends of the beam. To simulate the partial bonding behavior of the prestressed tendons, the EqualD of command can be used to release the translational freedom of the prestressed tendons along the length of the beam. The truss element is established between node 15 to 19, 16 to 20, 18 to 22, 17 to 21 to simulate energy-dissipating bars, using Barslip material. The joint region is simulated by setting internal and external nodes. There are shear springs between node 3 to 23, node 2 to 25, node 10 to 26, node 9 to 29 to simulate the shear deformation of joint. The axial expansion springs are set between node 27 to 31, node 28 to 32, node 20 to 29, node 21 to 30, node 19 to 27, node 29 to 33, node 22 to 28 and node 30 to 34 in order to simulate the axial deformation.

2.2. Numerical Simulation
Liu [11] carried out a pseudo-dynamic test on a two-stories two-span prestressed fabricated concrete frame structure, and studied the seismic performance of the structure through time history curves, hysteresis curves, ductility and stiffness.

The test frame storey is 1.6 m high and the beam span is 3.0 m. The dimensions of structure and reinforcement are shown in figure 2. The frame is tensioned by a prestressed steel strand with a stretching control stress of 0.75 fpt, the yield strength fpy=1811 N/mm², and the ultimate strength fpt=1974 N/mm². Non-prestressed tendons adopt hot rolled steel bars HRB335 and hoops use HPB235 hot rolled steel bars. The mechanical properties of the measured concrete members are shown in table 1. The mechanical properties of the measured steel bars are shown in table 2.

The frame test uses El Centro seismic wave. The test load is divided into three test conditions: 110gal, 220gal, and 320gal according to the amplitude of the seismic wave. During the test, vertical
loads are first applied to the top and the span of the column. After the load is stabilized, the horizontal load is used to simulate the seismic action.

![Frame size and reinforcement diagram](image)

**Figure 2.** Frame size and reinforcement diagram.

**Table 1.** Mechanical properties of specimen concrete.

| Name       | $f_{cu,k}$ (N/mm²) | $f_{c,k}$ (N/mm²) | $f_{c}$ (N/mm²) | $E_c$ (N/mm²) |
|------------|-------------------|-------------------|-----------------|--------------|
| Test frame | 44.5              | 29.78             | 21.27           | 33557        |

**Table 2.** Mechanical properties of prestressed tendons, steel bars and stirrups.

| Classification of steel | Diameter (mm) | Type of steel | Yield Strength (Mpa) | Ultimate strength (Mpa) | Elastic Modulus (Mpa) |
|-------------------------|---------------|---------------|----------------------|-------------------------|-----------------------|
| Prestressed tendon      | 15.24         | Steel strand  | 1811                 | 1975                    | 1.95×10⁵              |
|                         | 20            |               | 473                  | 605                     |                       |
| Non-prestressed tendons | 14            | HRB335        | 397                  | 535                     | 2.0×10⁵               |
|                         | 12            |               | 423                  | 586                     |                       |
|                         | 8             |               | 305                  | 463                     |                       |
| Stirrup                 | 6             | HPB235        | 345                  | 536                     | 2.1×10⁵               |

2.3. Numerical Simulation Results

The finite element model of the two-stories two-span prestressed fabricated frame structure is established by using the joint finite element model. The El Centro wave is used as the input data, and the calculation step is 0.02 s for inelastic time-history analysis. The numerical simulation results of the frame are compared with the experimental data to obtain the contrast diagram of displacement time history curve of the first and second storey of the structure under different load conditions.

The displacement time history curves of the first storey and second storey under different peak accelerations is shown in Figure 3. Overall, the simulation results of the displacement time history curve have the same trend and similar amplitude as the measured curve. It is indicated that the constructed finite element model of the joint can be applied to the framework finite element model, and the dynamic response of the frame structure can be reflected realistically. From the numerical simulation results, it can be further found that the peak displacement response of the frame structure
appears near 2.30 s and 4.53 s. This is slightly different from the time when the El Centro wave arrives its peak acceleration values. The peak value of the structural displacement response and the peak acceleration value of the seismic wave do not appear at the same time. The moment when the displacement of the structure reaches its maximum slightly lags behind the peak acceleration value of seismic wave, mainly determined by the spectral characteristics of the seismic wave and the natural vibration period of the structure.

Table 3 lists the test values and calculated values of the displacement of the prestressed fabricated frame stories under different load conditions. From the data in the table, it can be found that under the same working conditions, the simulated displacement value of the structure is slightly smaller than the experimental value. The main reason is that the bottom of the frame structure in the test is connected by bolts, and there is inevitably a gap. The finite element model build in OpenSees strictly assumes that the bottom of the frame column is completely embedded, which will not consider the existence of the gap in the test.

![Displacement time history curve under different PGA](image)

**Figure 3.** Displacement time history curve under different PGA.

| Loading condition | Loading direction | Displacement of first storey |  | Displacement of second storey |  |
|-------------------|-------------------|------------------------------|-----------------|------------------------------|-----------------|
|                   |                   | Simulation value \(\Delta_1\) | Test value \(\Delta_2\) | \(\Delta_1/\Delta_2\) | Simulation value \(\Delta_1\) | Test value \(\Delta_2\) | \(\Delta_1/\Delta_2\) |
| 110 gal           | Positive         | 2.98                         | 3.07            | 0.97                        | 5.86             | 6.07            | 0.97            |
|                   | Reserve          | 3.23                         | 3.48            | 0.92                        | 6.07             | 6.81            | 0.91            |
| 220 gal           | Positive         | 6.01                         | 6.33            | 0.95                        | 13.87            | 15.23           | 0.91            |
|                   | Reserve          | 7.23                         | 7.56            | 0.96                        | 15.23            | 16.82           | 0.91            |
| 320 gal           | Positive         | 13.21                        | 15.22           | 0.87                        | 26.34            | 29.99           | 0.88            |
|                   | Reserve          | 12.32                        | 14.81           | 0.83                        | 30.12            | 33.41           | 0.90            |
3. Parameter Analysis of the Joint

This section uses the pushover analysis to analyse the prestressed fabricated frame joint from five aspects: prestressed reinforcement area, energy-dissipating tendon area, the strength of concrete, the axial compression ratio, and the tensile control stress.

3.1. Prestressed Reinforcement Area

The joint models with prestressed reinforcement area of 181 mm$^2$, 362 mm$^2$, 544 mm$^2$ and 704 mm$^2$ were selected for pushover analysis. In figure 4, the hysteresis curve of the joint tends to be full as the area of the prestressed reinforcement increases. Due to the pre-stressing effect of the prestressed reinforcement, the residual deformation of the joint is small. In the first few cycles of loading, the greater the number of prestressed reinforcements configured, the smaller the residual deformation. With the increase of cyclic displacement, the prestressed reinforcement gradually yield, and the residual deformation will increase with the increase of the area of the prestressed reinforcement. In figure 5, with the increase of the area of the prestressed reinforcement, the ultimate bearing capacity of the joint has significantly improved. When the cyclic displacement of the joint is greater than 50 mm, the bearing capacity of the joint with a prestressed reinforcement area of 704 mm$^2$ is smaller than that of a joint with a prestressed reinforcement area of 544 mm$^2$. The main reason is that too much prestressed steel is configured to prematurely damage the concrete. The stiffness degradation curve of the joint when the joint is pushed down under different prestressed reinforcement areas is shown in figure 6. It can be seen from the figure that the joint stiffness at the same displacement increases as the area of the prestressed reinforcement increases. It can also be found that as the load displacement increases, the stiffness of the joints degrades significantly, and this trend becomes more pronounced as the area of the prestressed reinforcement increases.

![Figure 4. Hysteresis curve of joints under different prestressed reinforcement area.](image)

![Figure 5. Skeleton curve.](image)

![Figure 6. Stiffness degradation curve.](image)
3.2. Energy-dissipating Tendon Area

The joint models with energy-dissipating tendon area of 109 mm$^2$, 318 mm$^2$, 507 mm$^2$ and 706 mm$^2$ were selected for pushover analysis. In figure 7, the area of the reinforcement has a significant effect on the hysteresis curve of the joint. The area of the hysteresis loop of the joint increases with the increase of the area of the ordinary reinforcement. Increasing the area of the reinforcement can greatly improve the energy consumption capacity of the joint. At the same time, the increase in the area of reinforcement will increase the residual deformation. Therefore, in the design of joints, attention should be paid to the reasonable configuration of the area of reinforcement. In figure 8, the ultimate bearing capacity of the joint increases proportionally with the increase of the area of the reinforcement. When the area of reinforcement doubles, the ultimate bearing capacity of the joint increases by 18%, so reinforcement has a significant impact on the bearing capacity of the joint. Figure 9 reflects the effect of reinforcement area on the stiffness degradation curve of the joint. It can be seen from the figure that the influence of different energy-dissipating tendon areas on the stiffness degradation curve of the joint is roughly the same.

Figure 7. Hysteresis curve of joints under different reinforcement area.

Figure 8. Skeleton curve.

Figure 9. Stiffness degradation curve.

3.3. The Strength of Concrete

Joint models with concrete strength of 30 MPa, 40 MPa, 50 MPa, 60 MPa were selected for pushover analysis. In figure 10, the hysteretic energy dissipation curves of joints at different concrete strength levels have similar shapes. With the increase of the concrete strength, the larger the area enclosed by the hysteresis curve, indicating that the concrete strength can improve the energy consumption capacity of the joint. In figure 11, the concrete strength has a significant effect on the ultimate bearing
capacity of the joint. The ultimate bearing capacity of the joint with a concrete strength of 60Mpa is 2.5 times the ultimate bearing capacity of the joint with a concrete strength of 30 MPa. In figure 12, the strength of the concrete has a greater impact on the initial stiffness of the joint, and the higher the strength of the concrete, the greater the stiffness of the joint at the corresponding displacement. Under the initial cyclic displacement, the stiffness of the joint varies significantly with the strength of the concrete. When the joint undergoes a large cyclic displacement, the difference in joint stiffness is not significant.

![Figure 10. Hysteresis curve of joints under different concrete strength.](image)

![Figure 11. Skeleton curve.](image)

![Figure 12. Stiffness degradation curve.](image)

3.4. The Axial Compression Ratio
Axial pressure ratios of 0.2, 0.3, 0.4, 0.5, and 0.6 were selected for pushover analysis. In figure 13, when the axial pressure is relatively small, the hysteresis curve of the joint tends to be full as the axial pressure ratio increases, and the energy consumption capacity of the joint gradually increases. When the axial pressure ratio exceeds 0.4, the area of the joint hysteresis loop will decrease with the increase of the axial pressure ratio, reflecting the reduction of the joint's energy consumption capacity. When the axial compression ratio is less than 0.4, the axial compression ratio has little effect on the residual deformation of the joint. When the axial compression ratio exceeds 0.4, the residual deformation of the joint begins to increase and the joint stiffness decreases. In figure 14, as the axial pressure ratio increases, the trend of the joint skeleton curve is basically the same, and the ultimate bearing capacity of the joint increases first and then decreases. When the axial pressure ratio is around 0.4, the ultimate bearing capacity is maximum. When the axial pressure ratio exceeds 0.4, the joint will enter the plastic deformation earlier under the combined action of horizontal load and axial pressure, resulting in a lower ultimate bearing capacity of the joint under high axial pressure. In figure 15, the stiffness
degradation tendency of the joints under different axial compression ratios is roughly the same. As the displacement increases, damage is generated inside the joints, causing the joint stiffness to decrease.

![Hysteresis curve of joints under different axial pressure ratios](image)

Figure 13. Hysteresis curve of joints under different axial pressure ratios.

![Skeleton curve](image)

Figure 14. Skeleton curve.

![Stiffness degradation curve](image)

Figure 15. Stiffness degradation curve.

3.5. The Tensile Control Stress
Joint models with tensile control stresses of 0.4, 0.5, and 0.6 were selected for pushover analysis. In figure 16, the tensile control stress has a greater effect on the hysteresis curve of the joint. When the tensile control stress is small, with the increase of the tensile control stress, the residual deformation of the joint can be effectively reduced, and the shape of the hysteresis loop gradually transitions from an inverted S shape to a spindle shape. When the tensile control stress is too large, the joint will be prematurely damaged under complex stress conditions, which will increase the residual deformation of the joint and weaken the energy dissipation capacity of the joint. As shown in figure 17, the ultimate
bearing capacity of the joint increases first and then decreases as the tensile control stress increases. Reasonable tensile control stress makes the joint in a three-way stress state, which can effectively improve the ultimate bearing capacity of the joint. When the tension control is too large, the joint will plastically deform prematurely and cause the ultimate bearing capacity of the joint to decrease. In figure 18, the tensile control stress of the prestressed steel bar has no significant effect on the stiffness degradation curve of the joint. In summary, reasonable tensile control stress can control the residual deformation of the joints and improve the energy dissipation capacity of the joints. In the design of prefabricated frame joints, it is necessary to reasonably control the tension control of the prestressed reinforcement.

4. Conclusion
This paper proposes a finite element model of prestressed fabricated frame joint based on OpenSees. Firstly, the rationality of the proposed joint model was verified using experimental data. Secondly, parameter analysis were conducted from five aspects of prestressed tendon area, energy-dissipating tendon area, concrete strength, axial compression ratio and tensile control stress. The influence of five factors on the seismic performance of prestressed fabricated frame joints are discussed as follows:

1) The joint model based on OpenSees can well simulate the hysteretic performance of prestressed fabricated frame joint, and accurately evaluate the stiffness and deformation capacity of joint subjected to earthquake.

2) With the increase of the area of prestressed reinforcement, axial compression ratio and tension control stress, the hysteretic energy dissipation capacity and ultimate bearing capacity of the joints will
increase, but it shall be constrained to some extent, otherwise will cause the concrete to be prematurely damaged and reduce the ultimate bearing capacity.

(3) The concrete strength and energy-dissipating tendon area also have significant influence on seismic performance of prestressed fabricated frame joint.

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