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Finite element model of high strength concrete joint of weakening type steel

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Abstract. To improve the seismic performance of steel reinforced high strength concrete frame joints, we built a finite element model of the concrete frame joints to analyze the weak nodes. We established finite element models HSRC-A1 and HSRC-B1 to test the high-strength concrete joints. We used ANSYS program to find the constitutive concrete relations. Comparing the results of HSRC-A1 and HSRC-B1, it can be seen that the weakening of beam-shaped steel flange has a certain influence on the stress-deformation process of high-strength concrete joints. The simulation results are in good agreement with the experimental results, thus the model proposed in this paper has great applicable value.

Key words. Finite element analysis, high strength concrete joint, weakening type steel.

1. Introduction

The steel structure refers to a new type of structure between steel structure and reinforced concrete structure which is formed by rolling or welding steel in concrete. It is also equipped with structural steel bar and a small amount of reinforced steel bar [1]. The reinforced concrete components are equipped with profiled steel, and the steel content of the components has been greatly improved. Therefore, the steel reinforced concrete structure has the characteristics of high bearing capacity, high rigidity, good ductility and strong energy dissipation capacity [2]. The utility model is very suitable for the construction of large span, high rise and heavy load buildings, and it is particularly suitable for use in the construction of the earthquake zone [3].

At present, superplasticizers and highly active mineral admixtures are widely used. Under normal process conditions, high-performance concrete can be easily formulated [4]. High strength concrete is not easy to seepage. The bonding performance is good, and the synergistic ability between the materials is improved. At the same time, the increase of concrete strength improves the bearing capacity of steel reinforced concrete members. Therefore, under the premise that the strength of the component meets the requirements, the section size of the component can

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be further reduced, so as to reduce the weight of the structure, save the steel and increase the construction area. However, with the increase of concrete strength, its seismic performance becomes worse. This will inevitably affect the application of high-strength concrete in seismic engineering [5].

With the development and improvement of the finite element theory, foreign universities and research institutions have made good achievements in finite element analysis of steel reinforced concrete structures. Cornell University has developed a static and dynamic analysis program for 2D and 3D steel frames and steel reinforced concrete frames. In the process of finite element nonlinear analysis, the effect of stiffness degradation of steel members and composite members on the plastic properties of frame joints is considered.

By means of nonlinear finite element analysis of beam column connections in Chiba University, it is pointed out that the nonlinear behavior of nodes can be simulated accurately. It is shown that the finite element analysis is an effective tool to study the performance of nodes. K. Uchiba and H. Noguchi analyzed the finite element nonlinearity of a steel reinforced concrete frame. The results show that the bond behavior has an important effect on the performance of the nodes.

In recent years, a lot of researches have been done on the finite element analysis of steel reinforced concrete. In the process of force, the adhesion between the section steel and the concrete is small, which causes them to slip easily, especially after reaching 80 % of the ultimate strength. Therefore, the finite element model is used to simulate the different elements of the material, and the bonding element is set at the interface of different materials to simulate the bond slip behavior between the two materials. At the same time, it is pointed out that when the finite element analysis of steel reinforced concrete joints is carried out, the node is always in a state of plane stress [6]. The column steel and the flange frame form a good constraint on the node area, and the node zone slip is negligible. Moreover, in view of the difficulty of analysis, the influence of the bond slip between the steel bars, the steel and the concrete is neglected.

2. Finite element analysis of edge joints of high—strength concrete frame

At present, the application of high-rise, super-high-rise buildings and large-span structure medium-sized steel structure and high-strength concrete is becoming more and more common. However, the research on its seismic performance is relatively less. As a new type of seismic construction in recent years, the weakened joint has been widely used in the steel frame, and has gradually been applied to the steel reinforced concrete structure. The seismic test of the reinforced concrete frame joints shows that the dog bone is weakened by the steel frame joints, which can play the role of protecting the core area of the node, and can effectively improve the ductility and energy dissipation capacity of the joints. In the test, cyclic loading is applied to the beam end of the specimen. During the process of force, the steel web of the core area of the node first succumbs and enters the plastic flow stage. With the loading process, the beam near the core area of the specimen joint gradually enters the yield stage. Finally, when the ultimate load is reached, the concrete in the core area of the node is peeled off and the shear is destroyed.

2.1. Finite element modeling

In this paper, the finite element models HSRC-A1 and HSRC-B1 are established with reference to the test of the high-strength concrete joints of Hunan University. The axial compression ratio of the model is 0.2. The difference between HSRC-A1 and HSRC-B1 is that the shape of HSRC-B1 near beam ends is improved by dog bone. The core area of the joint is designed for the column steel, and the beam is cut off on both sides of the column and welded to the flange of the column steel. At the same time, the horizontal stiffening rib is set at the level of the beam flange of the steel web. The core area of the joint forms a closed flange frame. Beam longitudinal reinforcement and column longitudinal reinforcement link up in the core area of the node. The strength of the steel and the modulus of elasticity of the model are all determined by the measured strength values. The physical properties of steel materials are shown in Table 1.

Table 1. Test results of insulated resistance value (kΩ)

Steel type	Yield strength f_y (N/mm^2)	Ultimate strength f_u (N/mm^2)	Elastic modulus E_s ($\times 10^5$ N/mm^2)	Elongation (%)
I14	293.1	421.9	2.02	33.1
⌀6	415.7	603.7	2.15	23.7
⌀8	434.1	511.3	2.11	17.1
⌀20	500.8	637.9	2.05	12.4
⌀25	419.1	602.3	1.92	16.7

The finite element models HSRC-A1 and HSRC-B1 of high strength concrete joints are established with reference to test specimens HSRC-A1 and HSRC-B1. Model geometry and material strength are the same as the specimen. The steel reinforced high-strength concrete frame joint model is built by ANSYS's APDL parameterized command program. This modeling method can easily simulate and analyze the force and failure process of beam-column joints under different parameters by changing the specific parameters in the command flow, such as axial compression ratio, concrete strength and so on.

The steel reinforced concrete joints are composed of steel, concrete and steel. The materials are modeled by different units. The concrete is SOLID65 unit, the steel is SOLID45 unit, and the longitudinal reinforcement and all the stirrups are LINK8 units. In the actual engineering, the steel reinforced concrete joints are complicated, and the calculation process is also very complicated. So, ANSYS software is used to model the steel reinforced concrete. Before analysis, it should be simplified. This article makes the following assumptions:

(1) The node is always in a plane stress state and follows the small deformation assumption.

(2) In the steel part, the steel web resists shear, and the flange frame is used as a safe reserve. The steel reinforced concrete joints are mainly shear. According to the experimental analysis, it can be seen that the shear force borne by the frame flange is about 5 % of the shearing force of the steel web. It is generally regarded as a safe reserve without considering its shear effect.

(3) The slippage between the sections of steel, concrete and steel is not considered.

(4) The effect of the longitudinal reinforcement pin is not considered.

The elastic modulus E_s, the yield strength f_{y} and the ultimate strength f_{u} of the steel and steel bars can be determined by the steel material test. The Poisson ratio of all the steels in this paper is $\nu = 0.3$. The real constant of the steel element is the section area of its own, and the steel element cannot be set constant or constant is 0.

According to the constitutive relation of each material in the steel reinforced concrete joints, the corresponding stress and strain values of each material are input. The ANSYS program can automatically draw the constitutive relation curve of concrete, steel and steel bar. The constitutive relation of concrete is shown in Fig. 1, the constitutive relation curve of steel is shown in Fig. 2, and the constitutive relation of steel bars is shown in Fig. 3.

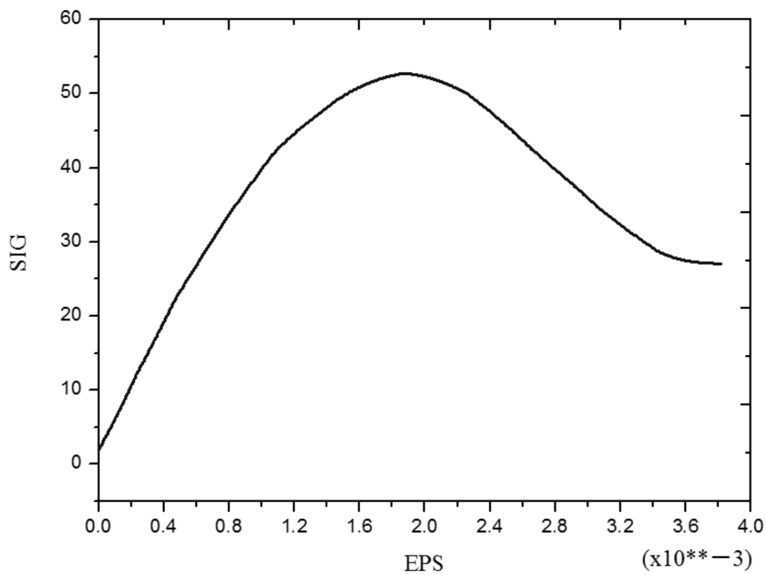

Fig. 1. Constitutive relation curve of concrete

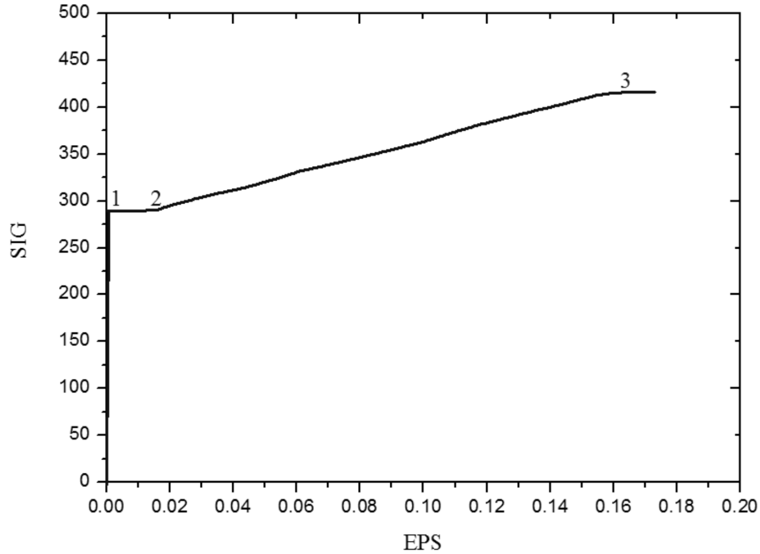

Fig. 2. Constitutive relation curve of steel

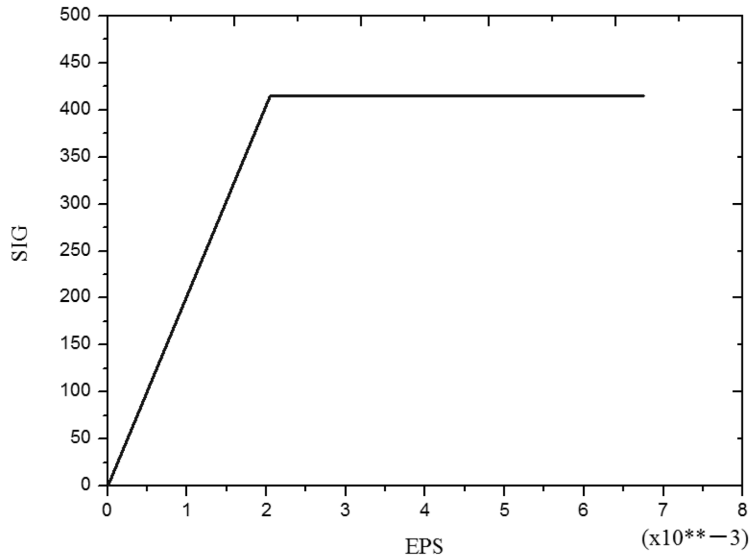

Fig. 3. Constitutive relation curve of concrete iron

2.2. Comparison between the calculated results and experimental results

The model loading point load-displacement curve is captured from the post-processing module, as shown in Fig. 4.

When the area of more than 50 % of the steel web reaches the yield strength, the load on the beam end is calculated for the yield load, and the corresponding beam end displacement is calculated for the yield displacement. When the model is damaged, the load on the beam end is the ultimate load, and the corresponding beam end displacement is the displacement under the ultimate load. The results of the finite element analysis of HSRC-A1 and HSRC-B1 are shown in Table 2.

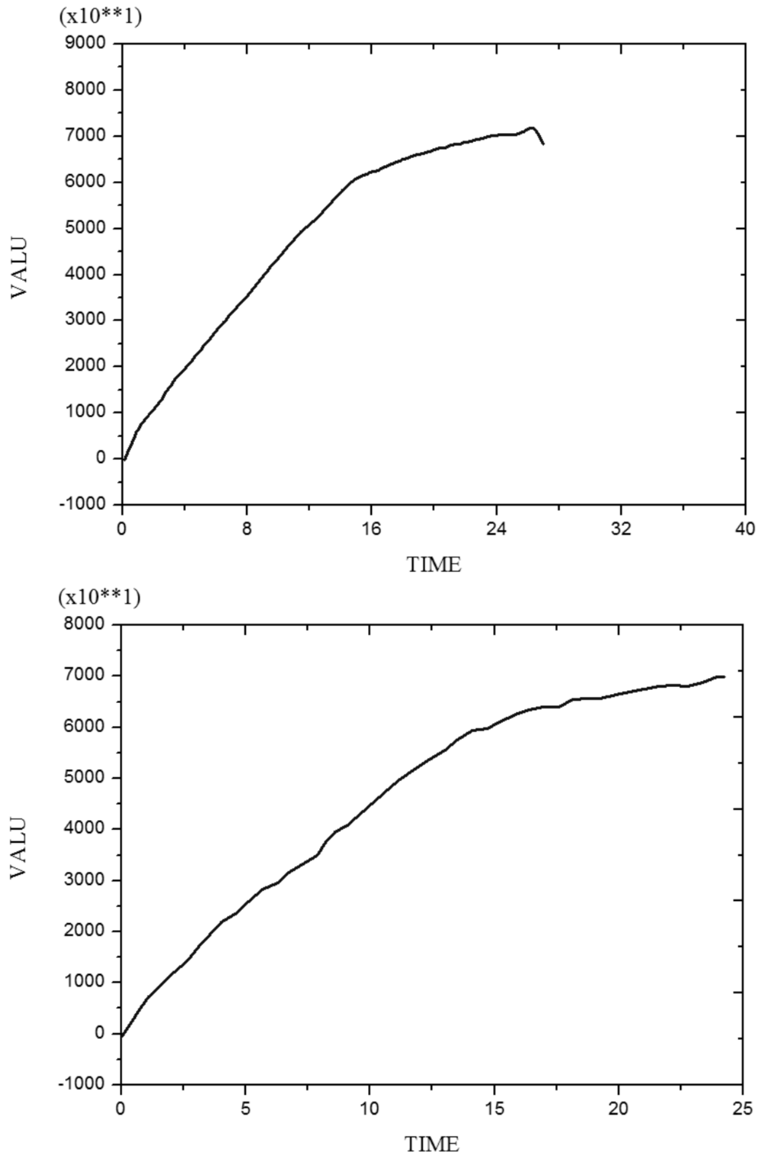

Fig. 4. Model HSRC-A1 and HSRC-B1 load-displacement curve: up–model HSRC-A1, bottom–HSRC-B1

Table 2. The results of finite element method

Number of the model	Yield load (kN)	Ultimate load (kN)	Yield displacement (mm)	Displacement under ultimate load (mm)	Failure form
HSRC-A1	122.35	144.8	17.7	26	Core shear failure
HSRC-B1	116.3	139.8	15.9	23.5	Core shear failure

By comparing the results of HSRC-A1 and HSRC-B1, it can be seen that the weakening of beam-shaped steel flange has a certain influence on the stress-deformation process of high-strength concrete joints. The yield load of the dog bone node is 116.3 kN, which is by 4.9 % lower than the yield of the normal specimen by 122.35 kN. Its ultimate bearing capacity is 139.9 kN. Compared with the ordinary model limit load 144.8 kN, it has no significant change. At the same time, comparing the calculated displacement of the HSRC-A1 and HSRC-B1 with the displacement corresponding to the ultimate load, it can be seen that the dog bone weakening of the nodal beam has little effect on the strength of the component.

The value of the yield loads, ultimate loads, yield displacements and ultimate displacements of HSRC-A1 and HSRC-B1 are shown in Table 3.

Table 3. Experimental results

Number of the model	Yield load (kN)	Ultimate load (kN)	Yield displacement (mm)	Displacement under ultimate load (mm)	Failure form
HSRC-A1	103.7	117.2	18.5	53.7	Core shear failure
HSRC-B1	95.6	114.0	16.8	57.6	Core shear failure

From the experimental results of HSRC-A1 and HSRC-B1, the yield load of dog bone specimen is reduced by about 5 % compared with the average specimen yield value of 114.0 kN. The ultimate load is 117.2 kN. Compared with the limit load of 114 kN, the difference is not big.

ANSYS is difficult to calculate the falling range of the load displacement curve. For convenient for comparing, the displacement corresponding to the ultimate load is compared with the displacement corresponding to the finite element calculation limit load, and assuming that the displacement ductility coefficient is the ratio of the displacement to the yield displacement corresponding to the ultimate load. Comparing the calculated results of ANSYS with the experimental results, the error is the ratio of the absolute value of the difference between the experimental value and the calculated value, as shown in Table 4.

From Table 4 and Table 5, it can be seen that the calculated value of the finite element is not much different from the experimental value, and the error is controlled within 20 %. The calculated bearing capacity is generally greater than the bearing capacity of the test. The reason for the analysis is that the material is approaching the ideal condition due to the finite element simulation, and the actual material condition, the specimen preparation process and the test process all affect the acquisition of the test result. When the finite element model is calculated, the monotonic load is applied. Therefore, the concrete test of the concrete crack is less, and the bearing capacity of the model is higher. In general, the finite element is well simulated in bearing capacity. The calculated displacement is smaller than the test value. The main reason is that the bond slip between steel and concrete is not taken into account, and the degradation of the overall stiffness of the specimen under repeated loading is not considered. Because the displacement ductility coefficient is the ratio of the displacement and yield displacement of the ultimate load, the displacement ductility coefficient in Table 5 is smaller. It cannot effectively reflect the ductility of steel reinforced high-strength concrete edge joints.

Table 4. Comparison of calculated values of loads with experimental values (kN)

Number of specimen		Yield load		Ultimate load		Failure form
		Experimental value	Calculated value	Experimental value	Calculated value	
HSRC-A1		103.7	122.35	118.2	147.8	Note 1
	Error	15.3 %		19.9 %		
HSRC-B1		95.6	116.3	114.0	139.8	Note 1
	Error	17.8 %		18.45 %		

Note 1: It is mainly shear failure of concrete core area.

Table 5. Comparison of displacement calculated values with experimental values (mm)

Number of specimen		Yield displacement		Diaplacement under ultimate load		The ratio of ultimate load displacement to yield displacement	
		Exper. value	Calcul. value	Exper. value	Calcul. value	Exper. value	Calcul. value
HSRC-A1		18.5	17.7	26.74	26	1.45	1.56
	Error	4.5 %		7 %		7 %	
HSRC-B1		16.8	15.9	24.7	23.5	1.47	1.57
	Error	5.6 %		5.1 %		6 %	

According to Table 5, it can be seen that the displacement ductility coefficient 1.47 of the model HSRC-A1 is not much different from that of the specimen HSRC-B1 displacement ductility coefficient 1.45 in the limit state. According to the experimental results, it can be seen that the displacement ductility coefficient of the specimen HSRC-B1 is about 15.9 % higher than that of the specimen HSRC-A1, which indicates that the dog bone weakening of the nodal beam can effectively improve the ductility of the node. In the limit state, the influence of the weakening of the girdle of the beam type steel flange on the ductility of the reinforced concrete edge node is not fully displayed. The nodal beam is weakened by dog bone, which can effectively improve the ductility of the "weak node".

The weakening of dog bone can effectively improve the ductility of weak joints, which is due to the nonlinear deformation of the plastic hinge at the end of the common node. However, the non-linear deformation of the plastic hinge can be developed at both ends of the beam at the same time, and the stress concentration is large due to the sudden change of the section. In a word, the use of the dog bone type to weaken the joint construction measures can improve the ductility of steel reinforced high-strength concrete joints, which is consistent with the test results.

3. Conclusion

In 2009, Hunan University conducted a seismic performance test on the edge of the dog bone steel reinforced high-strength concrete frame. On this basis, the finite element analysis software ANSYS was used to analyze the "weak nodes" of the steel reinforced high-strength concrete frame. At the same time, the influence of steel web on the mechanical properties and ductility of "weak node" of high strength concrete was analyzed. The following conclusions are drawn in this paper:

(1) Through the simulation test, the stress change process and the failure mode of the concrete and the steel in the joint are obtained. The core area of the joint steel web first reaches yield. Then, with the increase of the load, the beam steel tensile flange also gradually yield. Finally, the concrete in the core area is crushed, and the joints are destroyed by shear, which is in accordance with the design principle of the weak node.

(2) The finite element model is used as the auxiliary method of the test. The reasonable finite element model, the constitutive relation, the correct boundary condition and the simulation results obtained by the method are in good agreement with the experimental results.

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