Study on Bearing Capacity Influence Factors of the PBL Shear Connector

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Abstract. In order to study the main influencing factors of the ultimate bearing capacity of the PBL connector, the large-scale nonlinear finite element analysis software ABAQUS was used to establish the solid model of the PBL connector, and the accuracy of the model was verified by comparison with the test results. Based on this, the main influencing factors of the ultimate bearing capacity of PBL connectors are analyzed. The results show that it is feasible to apply ABAQUS to the finite element analysis of the mechanical properties of PBL connectors, which can be assisted by experiments and empirical formulas; The concrete strength, the diameter of rebar and the number of holes have a significant effect on PBL connectors’ force, but the diameter of holes has little effect.

1. Introduction

The steel-concrete composite structure can give full play to the advantages of the two materials when under load, the overall force is more coordinated, and has huge economic benefits and application prospects[1], so China has made breakthroughs in the fields of civil engineering, bridge engineering, etc. The traditional reinforced concrete structure turned to the steel-concrete composite structure. Among them, the shear connector located on the joint surface of the steel beam and the concrete slab can withstand the longitudinal shear force and the vertical lifting force between the two, which is the key to ensuring the normal operation of this structure. After decades of continuous research and practice by scholars from various countries, many economical and reliable forms of shear connectors have been developed. Among them, the most widely used in engineering is stud connectors. In the late 1980s, Leonhart et al.[2] first proposed the PBL connector. This new connector is composed of an open-hole steel plate and a concrete tenon. Through holes may or may not be provided in the holes. Compared with traditional stud connectors, PBL connectors have the advantages of high bearing capacity, high rigidity, and good fatigue resistance. Therefore, in recent years, they have been widely used in steel-concrete composite structures and hybrid bridges[3].

In engineering design, it is one of the key points to accurately calculate the shear bearing capacity of PBL connectors. Most domestic and foreign scholars mainly analyzed the influencing factors of its shear bearing capacity through experimental research. On this basis, it proposed to propose a formula for calculating the shear bearing capacity of PBL connectors by fitting regression[4,5]. However, due to the complicated stress state of the PBL connector, there are many factors affecting the bearing
capacity, and the cost of launching the test is high, and it takes a long time. It is impossible to comprehensively consider the influence of many parameters on the performance of the PBL connector, and it can only be observed. The cracking situation on the concrete surface, the internal failure form after the excavation of the outsourcing concrete slab and the strain at some points through the reinforcement, it is difficult to obtain the stress of the concrete during the loading process and the internal force on each section of the reinforcement, which is the PBL connector. The analysis of the force mechanism causes inconvenience, so it is necessary to complete the research through other methods, such as numerical simulation research. Through numerical simulation, the stress, strain, cracking and damage of the specimen at any position during the whole loading process can be obtained, and at the same time, the problem of insufficient quantity of the specimen can be made up. Existing relevant studies have proved that the finite element analysis method is applied to the PBL connector[6].

In view of the above problems, this paper will build a three-dimensional nonlinear finite element model of the PBL connector based on the large-scale finite element software ABAQUS to launch the test, and compare with the test results to verify the feasibility and accuracy of the numerical simulation method. On this basis, the main influencing factors of its ultimate bearing capacity will be analyzed.

2. Establishment of finite element model of PBL connector

In this paper, based on the finite element software ABAQUS, the PBL connection is established to launch the test solid model. The main components include concrete slabs and steel structures (shaped steel, rebar, stirrups).

2.1. Material constitutive

The constitutive model of concrete adopts the concrete plastic damage model. In the concrete damage model, the stiffness matrix can be reduced by calculating the damage factor to simulate the decrease or failure of the stiffness of the concrete unit; the concrete stress-strain relationship adopts "Construction Design Code of Concrete" (The calculation formula[7] in GB50010-2010), where the equivalent uniaxial compressive stress-strain expression of concrete is:

\[
\sigma = (1 - d_c)E_c\varepsilon_c
\]

\[
d_c = \begin{cases} 
1 - \frac{\rho_c n}{n+1+x^n} & x \leq 1 \\
1 - \frac{\rho_c}{\alpha_c(x-1)^2+x} & x > 1 
\end{cases}
\]

\[
\rho_c = \frac{f_{cr}}{E_c\varepsilon_{cr}}
\]

\[
n = \frac{E_c\varepsilon_{cr}}{E_c\varepsilon_{cr} - f_{cr}}
\]

\[
x = \frac{\varepsilon}{\varepsilon_{cr}}
\]

In the formula, \(\alpha_c\) is the parameter value of the concrete uniaxial compressive stress-strain relationship descending section, which is taken as 3.00 according to the specification; \(f_{cr}\) is the standard value of the concrete axial compressive strength, which is taken as 38.5N/mm2 according to the specification; \(\varepsilon_{cr}\) is the corresponding concrete peak strain and the value is 0.00203 according to the specification; \(d_c\) is the evolution parameter of the uniaxial compression damage of concrete.

The equivalent uniaxial tensile expression of concrete is:
\[ \sigma = (1-d_i)E_i \varepsilon \]  
(6)

\[ d_i = \begin{cases} 
1 - \rho_i \left[1.2 - 0.2x^2\right] & x \leq 1 \\
1 - \frac{\rho_i}{\alpha_i(x-1)^{1/3} + x} & x > 1 
\end{cases} \]  
(7)

\[ x = \frac{\varepsilon}{\varepsilon_{\text{pe}}}, \]  
(8)

\[ \rho_i = \frac{f_{\text{re}}}{E_i \varepsilon_{\text{re}}}. \]  
(9)

In the formula, \( \alpha \) is the parameter value of the concrete uniaxial tensile stress-strain relationship in the descending section, which is 2.81 according to the specification; \( f_{\text{re}} \) is the standard value of the concrete axial tensile strength, which is 2.85 N/mm² according to the specification; \( \varepsilon_{\text{pe}} \) is the peak strain, and the value is taken as 0.000118 according to the specification; \( d_i \) is the evolution parameter of concrete uniaxial tensile damage.

For other parameters of the plastic damage model, see Table 1. The value of the viscosity coefficient will affect the calculation time and convergence of the finite element model. Too many settings will affect the incorrect calculation results of the model, while too small settings will cause the model calculation to fail to converge. After repeated trials and calculations, the value of this article is 0.0001.

| Expansion angle | Eccentricity | \( f_{\text{re}}/f_{\text{so}} \) | \( k \) | Viscosity coefficient |
|-----------------|--------------|----------------|------|----------------------|
| 30              | 0.1          | 1.16           | 2/3  | 0.0001               |

The strength criterion of the steel structure adopts the Von Mises yield criterion; the penetration steel grade is HRB400, and the steel grade is Q345; the constitutive relationship adopts the trifocal constitutive model, and its stress-strain relationship is:

\[ \sigma = \begin{cases} 
E_i \varepsilon & \left(\varepsilon_i \leq \varepsilon_y\right) \\
f_y + 0.01E_y \left(\varepsilon_i - \varepsilon_y\right) & \left(\varepsilon_y \leq \varepsilon_i \leq \varepsilon_u\right) \\
f_u & \left(\varepsilon_i \geq \varepsilon_u\right) 
\end{cases} \]  
(10)

Where \( \sigma \) is the equivalent stress of the steel; \( E_i \) is the elastic model of the steel; \( f_y \) and \( \varepsilon_y \) are the yield stress and yield strain of the steel, respectively; \( f_u \) and \( \varepsilon_u \) are the ultimate stress and ultimate strain of the steel, respectively.

2.2. Unit selection and division
Since the key point of the simulation in the launch test is the contact relationship between concrete and steel beams and rebars, concrete, steel beams and rebars all use the linear reduced integral solid element C3D8R in the cell library, which can withstand large distortions Deformation, to avoid the shear self-locking effect of the unit under bending load, the calculation result is more accurate; and the stirrup mainly serves to restrain the concrete tenon, using a three-dimensional truss unit T3D2, this unit only bears axial force and can be embedded in concrete.

Use sweeping grid division technology to divide the unit, and perform mesh encryption processing on complex parts such as steel reinforcement, concrete tenon and concrete around the opening steel plate, the global grid is 20mm, and the minimum grid after local encryption is taken as 3mm, ABAQUS will automatically select the most complex surface as the starting surface for meshing.
2.3. Constraints and interactions
The surface-to-surface contact is set between the concrete unit, the shape steel unit and the penetrating steel unit. Since the oiling measures were taken to avoid the influence of the bonding force between the shape steel and the concrete during the test, when the friction is simplified by the Coulomb model, the shape steel and the tangential friction coefficient of the contact between the concrete is 0, and the tangential friction coefficient between the rebar and the concrete tenon is set to 0.5. The normal direction uses hard contact and allows the contact to separate; the stirrups are embedded constrained and buried by embedding. Into the concrete unit to simulate the real steel section. The detailed component interaction settings are shown in Figure 1.

2.4. Boundary conditions and loading simulation
In order to simplify the calculation and improve the calculation efficiency, this paper establishes a 1/4 model and imposes symmetric boundary conditions on the symmetry plane. The static implicit algorithm is used to control the loading according to the displacement, check the geometric non-linear option in the analysis step, and define a smooth curve coefficient of 0.5 to make the loading curve smoother and improve the convergence of the model calculation. The detailed boundary condition settings are shown in Figure 2.

2.5. Model validation
The comparison between the load-slip curve in the results of the finite element analysis and the test results are shown in Figures 3. It can be seen from the figure that the error of the ultimate bearing capacity calculated by the finite element is between 2% and 4%, and the average error is 3%, which is in good agreement with the test. The finite element model established in this paper can accurately simulate the overall mechanical behavior of the launch test specimen of the PBL connector.

3. The main influencing factors of the ultimate bearing capacity of PBL connectors
Previous studies have shown that the main force-bearing members of PBL connectors when they are under load are concrete tenons and rebars, and it can be seen that the strength of concrete, the diameter of holes, the diameter of rebars and the number of holes are the limits of PBL connectors. The bearing
capacity has a significant effect. In order to further study the influence of the above factors on the ultimate bearing capacity of PBL connectors, a single-factor variable parameter analysis is carried out on the ultimate bearing capacity of PBL connectors.

3.1. Concrete strength
Under the condition of ensuring other parameters and the same size of concrete, change the concrete grade and study the impact of the four concrete grades C40, C50, C60 and C70 on the bearing capacity of the PBL connector. The load-slip curve is shown in Figure 4.

It can be seen from the figure that for each increase in concrete strength, the ultimate bearing capacity of PBL connectors increases by approximately 80 kN, and the shear stiffness also increases, but the increase in the limit slip is not obvious. This is because when the PBL connector is under load, it mainly depends on the pressure of the concrete tenon in the hole and the pinning effect of the rebar. The increase of the concrete compressive strength will significantly affect the ultimate bearing capacity and shear rigidity of the PBL connector.

3.2. Hole diameter
Under the condition that the other parameters of the PBL connector remain unchanged, the diameter of holes is changed, and the influence of the three diameter changes of 50mm, 60mm, and 75mm on the bearing capacity of the PBL connector is studied. The load-slip curve is shown in Figure 5.

It can be seen from the figure that with the increase of the diameter of holes, the ultimate bearing capacity of the PBL connector has increased, and the shear stiffness and ultimate slip have also increased, but it is not obvious. This is because when the PBL connector is under load, it mainly depends on the pressure of the concrete tenon in the hole and the rebars. The compressive strength of the concrete tenon is mainly provided by the coarse aggregate. When the diameter of the hole is larger, the volume of the hole is larger. The higher the probability of coarse concrete entering the hole, the greater its ultimate bearing capacity and shear stiffness; at the same time, as the volume of the hole increases, the bearing area through the reinforcement also increases, and the shear stress decreases. Therefore, the bearing capacity of the test piece will be improved.

3.3. Rebar diameter
Under the condition that the other parameters of the PBL connector remain unchanged, change the diameter of rebar and study the influence of the four steel bar diameter changes of 0mm, 16mm, 20mm and 25mm on the bearing capacity of the PBL connector. The load-slip curve is shown in Figure 6.

It can be seen from the figure that after the PBL connector is configured to penetrate the steel bar, its ultimate bearing capacity increases by 68%, and the shear stiffness is also significantly improved; as the diameter of rebar increases, the ultimate bearing capacity of the PBL connector increases accordingly; when the diameter of rebar reaches 25mm, continue to increase the diameter of the steel bar, and the ultimate bearing capacity of PBL connectors does not increase significantly. This is because when the PBL connector is under load, it mainly depends on the pressure of the concrete
tenon in the hole and the pinning effect of the penetration of the steel bar. The shear bearing capacity of the concrete tenon is increased, but this effect is not unidirectional. When the hole diameter is fixed, the diameter of the penetration bar is too large, and the concrete coarse aggregate is difficult to enter the hole, which is not conducive to the force of the concrete tenon, so coordinated penetration is required. Reinforcement diameter, hole size and coarse aggregate particle size.

3.4. Number of holes
Based on the finite element model, when the other parameters of the PBL connector are unchanged, the number of holes is changed to study the effect of changes in the number of 1, 2, and 3 on the bearing capacity of the PBL connector. The load-slip curve is shown in Figure 7.

It can be seen from the figure that the ultimate bearing capacity of the PBL connector increases with the number of holes. When the number of holes increases from 1 to 2, the ultimate bearing capacity increases by 69%, but when the number of holes is greater than 2, For each additional hole, the ultimate load of the PBL connector only increased by 8%. This shows that When the number of openings is greater than 2, the effect of increasing the number of openings on the ultimate bearing capacity of the PBL connector is no longer obvious. The reason can be seen that when the porous PBL connector is under load, the stress of the concrete tenon in each hole is different. Some of the concrete tenon fails first, and the stress redistribution occurs on the holed steel plate, and then the other concrete tenon fails. Therefore, the ultimate bearing capacity of the porous connector is not simply the bearing capacity of the superimposed single-hole connector. In the calculation, it needs to be reduced according to the relationship between the number of openings, the diameter of holes, and the distance between the holes.

4. Conclusions
(1) This article provides an effective method for simulating the launch test of PBL connectors. The load-slip curve and failure shape of PBL connectors obtained by nonlinear finite element method are in good agreement with the test results. The use of ABAQUS to limit PBL connectors Meta-analysis is feasible and can assist in launching experiments to study PBL connectors.

(2) Considering the main influencing factors that affect the bearing capacity of PBL connectors, on the basis of the finite element model, a single parameter analysis of its ultimate bearing capacity is carried out by adjusting the four influencing parameter values of concrete strength, holes’ diameter, rebar’ diameter and number of holes. Among them, the concrete strength, the diameter of the rebar and the number of holes have a more obvious effect on the ultimate bearing capacity of the PBL connector, and the holes’ diameter has little effect on it.

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