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Study on Tensile Properties of Composite Structure Shear Connector

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Abstract: In this paper, the ABAQUS dynamic display analysis method is used to realize the quasi-static analysis of the welding nail. The correctness of the finite element model is verified by comparing with the existing experiments. The finite element simulation calculated four different nail lengths $h_s$, and the calculated simulation values were in good agreement with the experimental values. In the case of the failure mode, when the welding nail is too short and the length-to-diameter ratio of the welding nail is less than 5.92, the whole of the welding nail together with the broken concrete in the surrounding area is pulled out, and when the aspect ratio satisfies certain requirements, the welding nail is generated. Necking, the concrete slab is not broken, and the ultimate tensile bearing capacity is relatively close.

1. Introduction
The combined structure has been used in buildings and bridges for decades, because of its advantages of light weight, high bearing capacity and low beam height. Among them, the welding nail shear connector is widely used in the combined structure to resist the shear force at the interface between steel and concrete. Many scholars have conducted a large number of studies on the shear resistance and failure modes of the welding nail connection [1-5]. However, there have been few studies on the mechanical behavior of the combined structural interface of shear connectors under tensile or transverse bending moments. Xu et al. [10] found that cracks caused by bending have an adverse effect on the force of the welding nail.

In this paper, the non-linear finite element method is used to analyze the pull-out performance of the welding nail, which is compared with the LIN test. On the basis of this, the ultimate tensile strength, failure mode, damage, etc. of the different lengths of the welding nail are further analysis gives the value of an engineering proposal.

2. Finite element model
This paper refers to the experimental model of LIN[8] of Tongji University, using ABAQUS/Explicit for analysis.

The model components of this paper mainly include I-beams with stiffeners, concrete slabs, welding nails and steel bars as shown in Fig. 1. The concrete slab has a rectangular shape of $700 \times 500 \times 500$ mm. The root diameter of the welding pin is 22 mm, the diameter of the nail cap is 35 mm, and the height of the nail cap is 10 mm. As shown in Fig. 2, $h_s$ in the figure is the total height of the welding nail, and $h_{ef}$ is the effective height. This article mainly considers four different heights,
namely 100mm, 200mm, 300mm and 400mm. In the simulation process, in order to avoid the deviation of the results caused by the buckling instability of the I-beam during the drawing process, a sufficient number of stiffeners are placed on both sides of the I-beam.

Figure 1. Finite element model

Figure 2. Shows the size of the welding nail

In this paper, the concrete plastic damage model (CDP) in the ABAQUS material library is used to describe the mechanical behavior of concrete. The compression and tension of the CDP model need to be defined separately.

$$D_c = 1 - \frac{f_c}{\sigma_c}, \quad D_t = 1 - \frac{f_t}{\sigma_t}$$

(1)

The welding nail and the I-beam of this paper adopt the same constitutive structure, adopting the elastoplastic constitutive model, generally adopting three Line model.

$$\sigma = \begin{cases} E_s \varepsilon & (\varepsilon \leq \varepsilon_y) \\ \sigma_y + 0.01E_s(\varepsilon - \varepsilon_y) & (\varepsilon_y \leq \varepsilon \leq \varepsilon_u) \\ \sigma_u & (\varepsilon \geq \varepsilon_u) \end{cases}$$

(2)

In this paper, the HRB335 steel bar is used, and the 16mm diameter steel bar adopts a two-fold line constitutive model.

$$\sigma = \begin{cases} \varepsilon E_y & (\varepsilon \leq \varepsilon_y) \\ f_y & (\varepsilon \geq \varepsilon_y) \end{cases}$$

(3)

A consolidation constraint is applied below the concrete slab, $U_1 = U_2 = U_3 = UR_1 = UR_2 = UR_3 = 0$.

In this paper, a reference point RP is established directly above the I-beam with stiffeners, see Figure 1. The reference point is coupled to the upper surface of the I-beam. The loading method applies a tensile speed of 0.1 mm/s in the Ux direction at the reference point, and the loading speed cannot be too fast. It must be ensured that the kinetic energy of the structure cannot exceed 10% of the internal energy of the structure, thereby realizing the pseudo-static simulation[6].
This paper selects a universal contact in which the tangential direction is defined as a penalty function contact with a size of 0.4, which allows for arbitrary separation, sliding and torsion of the contact surface. The normal direction is a hard contact, and the stiffer stud is defined as the main face, and the concrete surface is defined as the slave face.

In this paper, the dynamic display analysis method is selected, and the quasi-static analysis of geometric nonlinearity and material nonlinearity is considered.

In order to obtain a cost-effective result, the paper considers the mass scaling and the expected time increment of 0.001s in the calculation. In order to increase the speed of the pseudo-static analysis, mass scaling is used in each incremental step, and different components adopt different mass scaling factors, which is beneficial to improve the efficiency of the solution.

Concrete slabs, I-beam with stiffeners and welding studs use a three-dimensional eight-node solid element (C3D8R), in which the concrete slab, the I-beam mesh with stiffeners are 20 mm in size, and the size of the stud is 8 mm. The steel frame adopts a three-dimensional two-node truss unit (T3D2), and the truss unit size is the same as that of the three-dimensional eight-node solid unit, both of which are 20 mm.

3. Finite element analysis

Pull-displacement

![Figure 3. Comparison of tension-displacement curves](image-url)
Table 1. Pulls simulation results

| Nail length (mm) | $T_u$ (kN) | Test/FE | ACI/FE | PCI/FE | $S_p$ (mm) | Failure mode |
|-----------------|------------|---------|--------|--------|------------|-------------|
|                 | Test      | FEA     | ACI    | PCI    |            |             |
| 100             | 98.7      | 98.7    | 75.5   | 83.5   | 1.01       | 0.77        | 0.85        | 0.8        | CF         |
| average         | 98.7      | 98.3    | 75.5   | 83.5   | 1.01       | 0.77        | 0.85        | 0.8        | —          |
| 200             | 174.8     | 176.4   | 197.2  | 177.5  | 0.99       | 1.11        | 1.01        | 10.72      | SF         |
| 300             | 172.8     | 175.2   | 2      | 5      | 0.99       | 1.12        | 1.01        | 16.45      | SF         |
| 400             | 171.9     | 175.9   | 197.2  | 177.5  | 0.98       | 1.12        | 1.01        | 21.76      | SF         |
| average         | 173.2     | 175.9   | 197.2  | 177.5  | 0.98       | 1.12        | 1.01        | 16.31      | —          |

CF in the table refers to concrete failure, and SF refers to steel failure.

Figure 3 shows that the finite element simulation and experiment are in good agreement and the trend is consistent. Regardless of the test or the simulated value of this article except for 100mm, the ultimate nail pull-out force is very close to the value of the PCI 5th specification [9], which is safer than the ACI 318-08 specification [10]. The value is small. The ultimate tensile force $T_u$ simulated in this paper is shown in Table 1. The finite element simulation value of the 100mm diameter welding nail is 98.3kN, and the simulated values of diameter 200mm, 300mm and 400mm are 176.4kN, 175.4kN and 175.9kN respectively. It can be seen that for 200mm The ultimate tensile force of 300mm and 400mm nails is very close, and the difference between them is very small. Moreover, the finite element simulation value is very close to the experimental value, indicating that the simulation method is reasonable.

Pallars and Hajjar suggest a minimum $h_{ef}/d_s$ for [7] to avoid concrete being pulled out and destroyed. The recommended formula is:

$$h_{ef}/d_s=\left\{\frac{(-0.91f_c'+155)d_s+(-30.5f_c'+5060)}{1000}\right\}$$

The minimum length-to-diameter ratio can be calculated to be 5.92. Only 100mm does not meet this requirement, and the remaining lengths meet the minimum aspect ratio requirement, so as to avoid the concrete being pulled out and destroyed.

4. Tensile stiffness and ductility

The analysis of the combined structure in the elastic range requires the use of tensile stiffness and can be solved in two ways. The first is to ignore the friction and bonding between the welding nail and the concrete, which is approximately expressed as tensile stiffness according to the uniaxial deformation of the welding nail, $K_t = E_s A_s / h_{ef}$. The second is based on the tension-displacement curve. When $T=0.5T_u$, the corresponding displacement $S$, $K_t = 0.5T_u / S_{0.5T_u}$. As shown in Fig. 4, the drawing of the welding nail is mainly divided into three stages. In stage 1, the pulling force and the displacement are approximately linearly increased. Phase 2 enters the plastic phase and the rate of growth slows until the ultimate pull is reached. In stage 3, the welding nail is damaged, the rigidity is reduced, and the downward trend begins to occur until the welding nail is completely broken.
5. Failure mode

From the perspective of failure mode, there are two main types of failure modes for different lengths. When the length is 100mm, the length to diameter ratio is 4.55, which corresponds to the failure of the first concrete. The studs were not pulled apart and pulled out of the concrete slab, at which point the studs did not yield. When the minimum aspect ratio is 9.09, the second type is the necking failure of the welding nail. As shown in (b), the welding pin yields, and the position where the necking fracture occurs is not the welding position, but the distance from the I-beam. A certain distance from the concrete interface. From the location of the fracture and deformation, the finite element of this paper can better simulate the structural failure mode of the welding nail under different lengths.
6. Conclusion
1. The welding nail shear joints show different failure modes under different tension ratios. When the length to diameter ratio is 4.55, the concrete is broken. When the aspect ratio is between 9.09 and 18.18, the nail is broken and broken.
2. The finite element simulation value of the 100mm diameter welding pin $T_u$ is 98.3kN, and the simulated values of diameter 200mm, 300mm and 400mm are 176.4kN, 175.4kN and 175.9kN respectively, which are very close, and the length has little influence on the ultimate bearing capacity.
3. The peak displacements of the 200mm, 300mm and 400mm diameter nails are 10.72, 16.45mm and 21.76mm respectively. As the length of the welding nail increases, the ductility is greatly improved.
4. ABAQUS display kinetics can be used for quasi-static analysis, the need to set the appropriate loading rate, and set the mass scaling factor of different components, can significantly improve the efficiency of analysis.
5. Concrete plastic damage model (CDP) can be used to simulate the failure mode of concrete.

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