Finite Element Analysis on Steel-Concrete Composite Beams Considering the Bond-Slip Effect on the Interface

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Abstract. In order to accurately simulate the bond-slip performance of steel-concrete composite beams, a trilinear stress-strain relation model was adopted to simulate the mechanical properties of steel. A uniaxial stress-strain relation curve was used to study the nonlinear mechanical behaviors of concrete. The resisting shear effects of studs and concrete in the bonding area were equivalent to nonlinear springs. Based on the energy principle, a calculation method of the interfacial bond stiffness of steel-concrete composite beams was proposed and the interfacial bond-slip constitutive relation of steel-concrete composite beams was given. Based on it, the three-dimensional finite element analysis model of steel-concrete composite beams was established by the finite element analysis software ANSYS, and the numerical simulations of existing push-out tests of composite beams were performed. By comparison, it can be seen that the results from finite element analysis in this paper are close to the experimental ones. It indicated that the finite element analysis model can accurately simulate the bond-slip action of the interface, and this model can be applied to the numerical calculation and analysis of steel-concrete composite beams.

Keywords. Composite beam, stress-strain relation, finite element, push-out test, bond-slip.

1. Introduction
As the shear connectors for steel-concrete composite beams, studs are widely used in practical engineering. Through the interaction between studs and concrete, the effective transmission of longitudinal shear stress at the interface of composite beams can be realized, guaranteeing the cooperative work between steel and concrete. At present, push-out tests are frequently adopted to study the interfacial bond performances of steel-concrete composite beams, and the evaluations of the bond performances were obtained, based on the experimental thrust-slip curves. For instance, Chapman [1] and his co-workers conducted an experiment on composite beams under concentrated and uniformly distributed loads and analysed the distribution of interface slip. Based on the test results, Nie J G [2] put forward the formula for calculating the yield and ultimate curvature of section considering the influences of shear connection degree. Su Q T [3] carried out static tests of composite box girders to calculate the relative displacement between steel and concrete. Xu C [4] conducted a serial of push-out tests on the bond performances between studs and concrete. Xue W et al. [5] carried out the experimental studies on the influences of stud corrosion rate, and analyzed the deflection and interface relative displacement of steel-concrete composite beams. However, due to the different arrangements of studs in actual projects with test models, the results of push-out tests cannot be completely applicable to practical engineering. Therefore, it is necessary to put forward a more
accurate finite element model to simulate the interface bond-slip action of steel-concrete composite beams.

2. Stress-Strain Relation of Steel
In the case of steel-concrete composite beams, a trilinear stress-strain relation model can be adopted to reveal the stress-strain relation of the steel beams. The mathematical expression is:

\[ \sigma_s = \begin{cases} E_s \varepsilon_s & \varepsilon_s \leq \varepsilon_y \\ f_y + E_a (\varepsilon_s - \varepsilon_y) & \varepsilon_y < \varepsilon_s \leq \varepsilon_u \\ 0 & \varepsilon_s > \varepsilon_u \end{cases} \]  

(1)

In Equation (1), \( \sigma_s \) and \( \varepsilon_s \) refers to the stress and strain of steel in the steel beam. \( E_s \) and \( E_a \) stands for the elastic and deformation modulus of steel. \( f_y \), \( \varepsilon_y \) and \( \varepsilon_u \) is respectively the yield strength, yield strain and ultimate strain of steel.

3. Stress-Strain Relation of Concrete
In the steel-concrete composite beams, the mathematical expression of stress-strain relation for concrete is:

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

(2)

In this equation, \( \sigma_c \) and \( \varepsilon_c \) respectively the stress and strain of concrete. \( E_c \) refers to the elastic modulus of concrete and \( d_c \) is the damage evolution index of the concrete under uniaxial stresses.

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

(3)

Here, \( \alpha_c \) is the descent phase parameter of stress-strain curves of concrete under uniaxial compression, as mentioned by Reference [6]. In the equation (3),

\[ \rho_c = \frac{f_c}{E_c \varepsilon_{c,r}} \]  

(4)

\[ n = \frac{E_c \varepsilon_{c,r}}{E_c \varepsilon_{c,r} - f_c} \]  

(5)

\[ x = \frac{\varepsilon_c}{\varepsilon_{c,r}} \]  

(6)

In the above equations, \( f_c \) refers to the uniaxial compressive strength of concrete, and \( \varepsilon_{c,r} \) is the peak compressive strain of concrete in accordance with \( f_c \), which can be derived from Reference [6].

4. Bond-Slip Constitutive Relation of the Interface Between Steel and Concrete
The existing research results indicated that the bilinear model in figure 1 can be used as the interfacial bond-slip constitutive relation of stud connectors. In figure 1, the ultimate bonding bearing capacity
$N_v^c$ and bond stiffness $k$ are two main parameters to be determined. According to Reference [7], when the ratio of a stud’s height to its diameter is greater than or equal to 4 (i.e., $\frac{h}{d} \geq 4$), its ultimate bonding bearing capacity is:

$$N_v^c = 0.43 A_s \sqrt{f'_c E_c} \leq 0.7 f A_s$$

(7)

Figure 1. Interfacial bond-slip constitutive relation of stud connectors.

In the above equation, $A_s$ is the cross-sectional area of stud, and $f$ is the design tensile strength of the stud. The arrangement and shear deformation of the studs at the interface between steel and concrete in composite beams were shown in figure 2, where $d$ and $h$ respectively refer to the diameter and height of the stud. $l$ stands for the longitudinal space of the studs in the direction of shear transmission. The calculating diagram of the stud and the shear deformation of the concrete in the bonding area were respectively shown in figures 3 and 4.

Figure 2. Arrangement and shear deformation of the studs.

Figure 3. Calculating diagram of the study.

Figure 4. Shear deformation of the concrete in the bonding area.

The relative displacement is supposed as $u$, then the shear strain between the stud and concrete can be expressed as follows:

$$\gamma = \frac{u}{h}$$

(8)

To further simplify the stud and concrete, their resisting shear action is equivalent to a spring with
The deformation energy of the equivalent spring $U_e$ is thus:

$$U_e = \int_0^u K u du$$  \hspace{1cm} (9)

The deformation energy of the spring $U_e$ equals the deformation energy of the stud $U_s$ plus the deformation energy of concrete $U_c$, as the following equation shows:

$$U_e = U_s + U_c$$  \hspace{1cm} (10)

The deformation energy of concrete in the bonding area is:

$$U_c = \frac{V}{h^2} \int_0^h G_c \gamma_x d\gamma_x$$  \hspace{1cm} (11)

where $G_c$ represents the shear modulus of concrete, and $V_c$ is the volume of concrete in the corresponding action area. $V_c = dh(l-d)$ can be deducted from figure 2. Substitute Equation (8) into Equation (11), the deformation energy of concrete in the bonding area can be calculated as:

$$U_c = \frac{V}{h^2} \int_0^h G_c u du$$  \hspace{1cm} (12)

The stud can be simplified as a cantilever beam, which is shown in figure 3, the deflection of the cantilever beam is:

$$\Delta = \frac{1}{3} w \left( \frac{x^4}{h^4} + \frac{4x^3}{h^3} + \frac{6x^2}{h^2} \right)$$  \hspace{1cm} (13)

from which the deformation energy of the stud can be obtained as:

$$U_s = \frac{1}{2} \int_0^h E_s I_s \left( \frac{d^2\Delta}{dx^2} \right)^2 dx$$  \hspace{1cm} (14)

In this equation, $I_s$ refers to the cross-sectional moment of inertia of the stud, i.e. $I_s = \frac{1}{64} \pi d^4$. If the second derivatives on both sides of Equation (10) are taken, i.e. $\frac{\partial^2 U_e}{\partial u^2} = \frac{\partial^2 U_s}{\partial u^2} + \frac{\partial^2 U_c}{\partial u^2}$, it is obvious that $K = \frac{\partial^2 U_e}{\partial u^2}$. Then Equation (15) can be derived:

$$K = \frac{\pi d^4}{20h^3} E_s + \frac{d(l-d)}{h} G_c$$  \hspace{1cm} (15)

Given that the interfacial bond stiffness per unit length $k = \frac{K}{l}$, it can be obtained that:

$$k = \frac{\pi d^4}{20h^3} E_s + \frac{d(l-d)}{hl} G_c$$  \hspace{1cm} (16)

5. Finite Element Analysis of the Push-out Tests of Steel-Concrete Composite Beams

In this paper, a three-dimensional numerical analysis model of push-out tests of steel-concrete composite beams were established by using the general finite element analysis software ANSYS. In the model, the steel beam was simulated by the eight-node solid element solid185, and concrete by solid65. The bond-slip performance of stud connectors at the interface between steel and concrete was
simulated by the three-dimensional nonlinear spring element combin39. In practical projects, it is necessary to set appropriate transverse reinforcement in steel-concrete composite beams to prevent concrete from splitting failure in the bonding area of composite beams due to the interactions between studs and concrete. Consequently, in the finite element model, the integral modeling method of reinforced concrete was adopted, and the reinforcement ratio of transverse reinforcement was set in solid65 element of concrete in bonding area to consider the anti-splitting effect of transverse reinforcement. The stiffness of combin39 can be calculated as Formula (16), in which the interface bonding stiffness per unit length \( k \) was gained. Then, by using the element grid length \( L \) along the component longitudinal direction at the interface, the value of spring stiffness given to each combin39 element was \( kL \). The constitutive relations of steel and concrete were calculated according to the methods in Section 2 and Section 3 of this paper. The geometric size and material strength of the specimens was in accordance with the parameters provided in Reference [4]. The finite element analysis model of push-out tests of steel-concrete composite beams is shown in figure 5.

![Finite element analysis model of push-out tests of steel-concrete composite beams.](image)

A comparison between the results from the finite element analysis and the tests results was illustrated in figure 6. From figure 6, it can be seen that the results were rather close each other. Therefore, the conclusion can be drawn that the finite element analysis model proposed in this paper can accurately simulate the bond-slip action at the interface between steel and concrete.

![Comparison between FEA results and the test results.](image)

6. Conclusions
In this paper, the nonlinear mechanical behaviors of steel and concrete in composite beams were
respectively simulated by adopting the stress-strain relation model of steel and concrete. Based on the energy principle, a method for calculating the interfacial bond stiffness of steel-concrete composite beams was proposed. A three-dimensional finite element analysis model of steel-concrete composite beams was also established. Then a numerical analysis of existing push-out tests was carried out. By comparison, it can be seen that the results from the finite element analysis in this paper were close to the experimental ones, which suggests that the established three-dimensional finite element analysis model is accurate, and that this model can be applied to the numerical calculation of steel-concrete composite beams.

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