Analysis of Bearing Capacity of Steel-Concrete Composite Beams Considering Interface Slip Effect

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Abstract. Bearing capacity of the composite beam is analysis with three nonlinear finite element methods in the thesis, in which Hognostand's uniaxial compression equation and BGIN model was applied to represent the constitutive relationship of concrete and steel in consideration of nonlinearity of concrete and the yield and strengthening characteristics of steel respectively. The interface slip between steel and concrete in composite beam is reasonably taken into account in the analysis with two methods. Those methods are compared according to the finite element analysis result, and the character of those methods are discussed and verified with the experimental result.

Keywords. Composite beam, bearing capacity, solid stud, node binding, spring connection.

1. Introduction
Building a reasonable model of interface between steel and concrete is the key to analysis bearing capacity of composite structure. If the interface slip between different materials cannot be reasonably simulated, the accuracy of finite element analysis will be greatly reduced. There are three commonly methods used to simulate the interface of steel-concrete composite beams [1-3], including interface binding, spring element connection and solid stud embedded concrete. Based on the existing composite beam test data, the simulation effect of the above three kinds of composite beam interface model are verified in this article.

2. Introduction of Experiment and Finite Element Model
The bearing capacity of steel-concrete composite beams is analysis with the finite element method in three methods. An experimental beam with is chosen for the corresponding finite element simulation, and the finite element simulation data are compared with the experimental results [4, 5]. Figures 1 and 2 show the cross and longitudinal section of a test beam respectively. The span of the beam end is 2 m. The concrete deck and steel beam are made of C20 concrete and Q235 steel respectively. The concrete bridge deck and steel beam are connected by 20 double row studs with the diameter of 13.6 mm and the longitudinal spacing of 200 mm. Data in table 1 is the material parameters of the test specimens.
It is very important to select a reasonable constitutive relation for the accuracy of the finite element simulation analysis. The constitutive relationship of concrete and steel is chosen according to the measured results of material properties in the experiment. A damage plastic model of is applied to simulate the concrete bridge deck to describe different characteristics of concrete compressive and tensile strength. The relevant material parameters will be chosen according to the recommended values in references [6, 7]: the expansion angle is 30 °, the eccentricity is 0.1; the ratio of biaxial to uniaxial compressive strength is 1.16; the yield surface shape parameter $k$ is 0.667; and the viscosity parameter is 0. The constitutive relation of concrete will be expressed by Hognostand's uniaxial compression equation, including the ascending and descending segment as follow:

$$\begin{align*}
\sigma_c &= f_c \left[2 \left( \frac{\varepsilon}{\varepsilon_0} - \left( \frac{\varepsilon}{\varepsilon_0} \right)^2 \right) \right] & 0 < \varepsilon \leq \varepsilon_0 \\
\sigma &= f_c \left( \frac{\varepsilon_u - 0.85\varepsilon_0 - 0.15\varepsilon}{\varepsilon_u - \varepsilon_0} \right) & \varepsilon_0 < \varepsilon \leq \varepsilon_u
\end{align*}$$

(1)

where: $f_c$—peak stress of concrete under uniaxial compression (MPa); $\varepsilon_0$—the strain corresponding to the peak stress, taken as $\varepsilon_0 = 0.002$; $\varepsilon_u$—the ultimate compressive strain, taken as $\varepsilon_u = 0.0033$. For the C20 grade concrete (13.4 MPa) in this model, the compressive stress-strain curve is shown in figure 3.
The modulus of the material in the elastic stage and the plastic stage are determined from the slope of the two lines respectively:

$$\sigma = \begin{cases} E_s \varepsilon & \varepsilon < \varepsilon_y \\ f_y + E'_s (\varepsilon - \varepsilon_y) & \varepsilon \geq \varepsilon_y \end{cases}$$

(2)

where: $f_y$ - yield strength of steel (MPa); $\sigma$ - elastic modulus of steel (MPa); $E$ - tangent modulus of steel after yielding (MPa), taken as 0.01; $\varepsilon_y$ - yield strain of steel.

![Figure 4. Constitutive relation model of steel.](image)

The steel beams and concrete slabs in composite beams are connected as a whole with shear studs which bear vertical force and longitudinal shear force [9, 10]. When the spring element is introduced to simulate the connection effect of stud, the load displacement curve of the stud should be defined. The calculation equation of Ollgaard is introduced into equation (3):

$$V = V_u (1 - e^{-mS})^n$$

(3)

where: $V$ - The load on single stud (N); $V_u$ - ultimate shear capacity of single stud (N); $S$ - Interface slip (mm); $m, n$ - constant, where $m= 0.4, n= 0.7$.

The calculation equation of shear ultimate bearing capacity of single stud is as follows:

$$V_u = 0.43A_s \sqrt{f_c E_c} \leq 0.7A_y f$$

(4)

where: $A_s$ - cross section area of stud (mm$^2$);

$E_c$ - elastic modulus of concrete (MPa);

$f_c$ - Is the design value of concrete axial compressive strength (MPa); $\gamma$ - the ratio between the minimum tensile strength of stud and its yield strength, taking 1.67.

According to equation (4), the ultimate bearing capacity of the stud in the experiment beam is 36.5 kN, and the shear slip curve of the stud is drawn with equation (3), as shown in figure 5.

![Figure 5. Shear slip curve of stud in test beam.](image)
3. Finite Element Model of Combination Beam

In the following analysis, the concrete is simulated by 8-node 3D solid element to reflect the material nonlinearity of concrete, and the steel beam is simulated using shell element. The interface of the two materials is simulated by the three following methods. One way is that the stud is simulated with three-dimensional solid element, in which the bottom of the stud is bind with the top of the steel beam, and the upper end inserted into the concrete to transfer the shear force at the interface through the root of the stud. The other is to use the spring element to simulate the stud, as shown in figure 6. The spring element consists of two nodes. With the load displacement curve of the spring element, the slip characteristics of the shear connector can be simulated, and the slip and nonlinearity in three directions can also be taken into account at the same time. To simplify the computation process, only the longitudinal slip along the beam length is considered in the model. The vertical and transverse stiffness of the spring element is set as a large value to ignore the vertical and horizontal slip. In addition, the vertical and transverse degrees of freedom of the joints corresponding to the spring element on the steel beam and concrete slab element can also be coupled [11]. The third modeling method is to bind the top of the steel beam and the bottom of the concrete slab directly in the finite element model, assuming that they will not be separated under the loads.

![Spring element for Shear connector.](image)

In order to avoid stress concentration and obtain better result in the analysis, the actual loading point is coupled with a surface in the middle of the composite beam and the displacement control loading is adopted to get the more accurate results in the model. The displacement increment of each analysis step is set as 0.5 mm, and the maximum vertical displacement of the test beam is 28.5 mm step by step. The finite element models based on the three simulation methods are consistent except for different interface simulation methods. The element division of the finite element model is shown in figure 6 and figure 7.

![Mises stress of binding connection model under ultimate load.](image)

4. Comparative Analysis with Three Models

The displacement control method is adopted in the finite element analysis to evaluate the ultimate bearing capacity of the composite beam [12]. The ultimate bearing capacity results of experiment result and the three models are listed in table 2.

| Model            | Experimental result/kN | FEM Result/kN | Absolute error /kN | Relative error |
|------------------|------------------------|---------------|--------------------|----------------|
| Solid stud       | 101                    | 98.2          | 4.8                | 4.7%           |
| Spring connection| 101                    | 96.3          | 6.7                | 6.5%           |
| Binding connection| 123.2              | 123.2         | 22.2               | 22%            |
As shown in the table 2 that the ultimate load of solid stud model and spring connection model is slightly smaller than the experimental results, and the relative errors are 4.7% and 6.5% respectively. The difference is due to the neglect of cohesion between steel beam and the concrete slab in the computation, so the bearing capacity is relatively lower. At the same time, there are some differences between the material constitutive model and the experimental beam. The relative estimation error is less than 22%. It can be shown from figure 7 that the yield region of steel beam under ultimate load of the binding connection model is larger, which reveals that the overall performance of this model is better than the other two models. The load deflection curve comparison diagram of the test beam obtained through finite element calculation and test are shown in figure 8. It can be seen from the figure 8 that in the early stage of loading, the structure basically presents the trend of elastic deformation.

![Figure 8. Comparison of load displacement curves.](image)

When the load reached about 80% of the ultimate load, the curve has an inflection point. It shows that the bearing capacity of the beams simulated by the three modeling methods is slightly larger than the experimental value in the elastic stage. As mentioned above, the combination effect and stiffness of composite beams are enhanced because the slip between interfaces is ignored, which leads to the difference between the experimental beam and the finite element model. As shown in figure 8, under the same load, the deflection of the composite beam calculated by the binding model is smaller than that of the other two models. According to the computational result, the effect of slip on the mechanical behavior of composite beams remains small in the elastic stage, but it becomes very large in the elastic-plastic stage. It is found that the computational results obtained with stud solid modeling method are in good agreement with the experimental one, although the computational cost is high.

In order to clarify the slip characteristics of different composite beam models at the interface, the load slip curves of the model beam end, 400mm and 800mm away from the beam end and the distribution of the ultimate load sliding along the beam length are shown in figures 9 to 12. Because the binding connection model will not slip at the interface, only the solid stud model and spring connection model are compared. It can be seen from the figure that in the early stage of the test, due to the bonding between the concrete slab and the steel beam interface, no sliding occurred in the experiment. The bond effect of the interface is not counted to ensure the convergence, so the slip will appear in the early stage of loading. With the increase of load, the influence of bond between interfaces decreases gradually. When the ultimate load is reached, the computational slip value is close to the experiment result. The load value of solid stud model is usually slightly larger than that of spring connection model, and the trend of load slip curve obtained with the two models are consistent with the experimental results, and the computational value of slip under ultimate load is also basically the same as that of the experiment.
Figure 9. Load A slip diagram.  
Figure 10. Load B Slip diagram.  
Figure 11. Load C slip diagram.  
Figure 12. Slip distribution under ultimate load.

5. Conclusion
According to the results of above analysis, solid stud modeling or spring element which is used to simulate connector will get more accurate behavior of composite beam. If it is possible to obtain the load slip curve of shear connectors through experiments, it is recommended to use spring element to simulate the connection between composite beam interfaces, which can not only simplify the modeling effect, but also obtain reliable results. Cluster type stud is often used to reduce the influence of concrete shrinkage and creep in the composite beam bridge design. In this case, if the solid stud modeling method is used to analyze the mechanical characteristics of composite beam bridge, the load on model will be very large that may lead calculation result not to converge. Spring element provides a feasible way to obtain reliable computational results with a reasonable load slip curve.

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