Research on Model Test Program of Steel-concrete Composite Connection

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Abstract. Based on the study on existing experimental research on steel-concrete composite connection, the experiment setup of the steel-concrete composite connection with cells of the Yongjiang River Bridge, is presented. The design theory of model test, comparison of model test program, design of steel and concrete, design of shear connectors and the deviation of model test are discussed. Especially for the design issues of shear connectors in a scale model, the finite element model of the small size of the shear connectors release test was established to calculate carrying capacity and shear stiffness. The constitutive relationship and failure criteria are discussed. The designing method of shear connectors in scale model test was proposed.

Introduction

With rapid constructing of high-speed railway in China, the railway hybrid girder cable-stayed bridge has been widely built to cross large bodies of water, due to its competence for rigidity and mass distribution[1]. The steel-concrete composite connection is the important part of hybrid girder cable-stayed bridge using to connect the concrete beam and the steel beam. At present, there are many large-span bridges using steel-concrete composite beam in our country, such as Shanghai Xupu Bridge, Shantou Queshi Bridge, Zhoushan Taoyaomen Bridge, Edong Bridge and so on[2,3]. The steel-concrete composite connection with cells,a critical part for hybrid girder cable-stayed bridge, is widely used to meet the transmission of internal forces and deformation caused by the high speed trains. Due to the complicated structural form and material properties, the mechanical behavior of the steel-concrete composite connection with cells is still unclear. Currently, there are still few literatures regarding the research on steel-concrete composite connection with cells. It is necessary to research the steel-concrete composite connection through the model test. The model test program is the key of model test.

Design Theory of Model Test

Depending on the size relationship between the test model and the original structure, model test can be divided into full-scale model test and scale model test. Whichever model test to research the mechanical behavior, it is necessary to exist the similarity between the test model and the original structure.

Geometric similarity: the length, width, height, area, volume, modulus of section, moment of inertia of model and original structure should satisfy the formal equation (1)~(5):

\[
\frac{\ell_m}{\ell_y} = \frac{b_m}{b_y} = \frac{h_m}{h_y} = S_1 \quad (1) \quad \frac{A_m}{A_y} = S_2 \quad (2) \quad \frac{V_m}{V_y} = S_3 \quad (3) \quad \frac{W_m}{W_y} = S_4 \quad (4) \quad \frac{I_m}{I_y} = S_5
\]
where \( \ell_m, \ell_y, b_m, b_y, h_m, h_y, A_m, A_y, V_m, V_y, W_m, W_y, I_m, I_y, A_m, A_y, V_m, V_y \) are the length, width, height, area, volume, modulus of section, moment of inertia of model and original structure. \( S_i \) is similarity ratio.

Mass similarity: the mass and density of model and original structure should satisfy the formula equation (6)~(7):

\[
S_m = \frac{m_m}{m_y} = \frac{\rho_m}{\rho_y} \quad (6) \quad S_p = \frac{\rho_m}{\rho_y} = \frac{m_m}{S_y} = \frac{S_m}{S_i} \quad (7)
\]

where \( S_m, S_p \) are the similarity ratio of mass and density. \( m_m, m_y, \rho_m, \rho_y \) are the mass and density of model and original structure.

Load similarity: the concentrated load, line load, surface load, bending moment and self-weight of model and original structure should satisfy the formula equation (8)~(12):

\[
S_p = \frac{m_m g}{m_p g} = S_m \quad (8) \quad S_w = \frac{m_m \times g \times l_m}{m_p \times g \times l_p} = S_m / S_i \quad (9) \quad S_q = \frac{m_m \times g \times l_m^2}{m_p \times g \times l_p^2} = S_m / S_i^2 \quad (10)
\]

\[
S_M = \frac{m_m \times g \times l_m}{m_p \times g \times l_p} = S_m \times S_i \quad (11) \quad S_{mp} = \frac{m_m \times g \times l_m^3}{m_p \times g \times l_p^3} = S_m \times S_i^3 \quad (12)
\]

where \( m_m, m_p, l_m, l_p \) are the mass, \( t \) the length, of model and original structure. \( S_p, S_w, S_q, S_M, S_{mp} \) are similarity ratio of the concentrated load, line load, surface load, bending moment and self-weight.

**Comparison of Model Test Program**

The Yongjiang Bridge is a hybrid girder cable-stayed bridge. The main span is 468m. The length of Yongjiang Bridge steel-concrete composite connection is 7.35m. The height of it is 5m. According to experimental purposes, the similarity theory and test sites, equipment loading conditions, three model test programs are proposed.

1. The same similarity ratio was used in the longitudinal, transverse and vertical. The same similarity ratio is 1:5. The program can accurately reflect the force of each member, the difficulty of manufacture can be solved by design.

2. The different similarity ratios were used in the longitudinal, transverse and vertical. The similarity ratio of the longitudinal is 1:5, the transverse is 1:5, the vertical is 1:2. The program can accurately reflect the force of each member, and it is not difficult to make the model. But the program cannot reflect the force mode of the original structure.

3. Selecting the top and bottom cell located on both sides of the web design the model according to the similarity ratio, the similarity ratio is 1:2. The program can reseach the stress distribution and transfer mechanism of shear studs, bearing plate, and the action between the steel and concrete. but it cannot reflect the shear lag effect of steel-concrete composite connection with cells.
Figure 1. The overall layout of model.

Based on the above research, the first test program was adopted. It can accurately reflect the force of each member and the shear lag effect of steel-concrete composite connection with cells. The overall layout of model was shown in Figure 1.

**Design of Steel and Concrete**

According to the test purposes, the design principles of steel and concrete are as follows: The stress of test model and the original structure is same. The size of top, bottom and web plate is one-fifth of the original structure. The reinforcement ratio of model is the same as the original structure. The size, area, and moment of inertia meet similarity theory. The design result of each plate was shown in Table 1. The design deviation of the section properties were shown in Table 2.

**Table 1. The design result of each plate.**

<table>
<thead>
<tr>
<th>NO.</th>
<th>member</th>
<th>Plate thick of original structure</th>
<th>Plate thick of test model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top plate</td>
<td>28mm</td>
<td>6mm</td>
</tr>
<tr>
<td>2</td>
<td>Bottom plate</td>
<td>28mm</td>
<td>6mm</td>
</tr>
<tr>
<td>3</td>
<td>Web plate</td>
<td>28mm</td>
<td>6mm</td>
</tr>
<tr>
<td>4</td>
<td>Bearing plate</td>
<td>60mm</td>
<td>12mm</td>
</tr>
<tr>
<td>5</td>
<td>Perforated plate</td>
<td>28mm</td>
<td>12mm</td>
</tr>
</tbody>
</table>

**Table 2. The design deviation of the section properties.**

<table>
<thead>
<tr>
<th>Beam segment</th>
<th>area (cm²)</th>
<th>Moment of inertia (cm⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>theory</td>
<td>practice</td>
</tr>
<tr>
<td>Steel beam</td>
<td>872</td>
<td>870</td>
</tr>
<tr>
<td>Stiffness transition segment</td>
<td>1385</td>
<td>1360</td>
</tr>
<tr>
<td>Steel-concrete composite connection</td>
<td>1750</td>
<td>1740</td>
</tr>
</tbody>
</table>

**Design of Shear Connectors**

Mechanical properties of shear connectors is an important factor which effects the steel concrete force behavior. Shear connectors design in scale model is regarded as the key of the steel-concrete composite design. Therefore, the study about a similar design method of shear connectors between model and original structure is needed before the test model design. Shear load bearing capacity and slip curves are two important indicators to measure the static mechanical properties of shear connectors. Launch test are the best way to study these two indicators, but the full-scale launch test is time consuming and uneconomical. In recent years, fine finite element analysis becomes a common
way to evaluate the shear connectors’ static metrics and replaces launch test gradually. Both overseas and domestic scholars study[4,5] show that as long as the components of the material model is selected appropriately, and the boundary conditions are handled properly, it is easy to get the more accurate indicators of static shear connectors through fine finite element analysis. This paper set up the refined finite element model of routine launch test of shear connectors, using previous test data to verify the correctness of finite element modeling methods. By means of this modeling methods, the finite element models of original bridge steel-concrete segment conventional shear connectors and scale model steel-concrete composite segment small size shear connectors are established. The carrying capacity and shear stiffness need to be calculated. The load-slip curve need to be drawn up. According to the carrying capacity and shear stiffness comparison of conventional shear connectors and the small size of the shear connectors, the similar design method of the scale model tests of shear connectors are proposed.

**Finite element modeling.** Nonlinear finite element model of push-out tests is established by ANSYS finite element program, as shown in Figure 2~3.

The material constitutive relationship, failure criteria, element selection and confirmation of boundary conditions are presented below.

**The constitutive relationship and failure criteria.** According to the characteristics of the shear connector test and relevant research materials, the Hognestad’s empirical formula is chosen to formulate the constitutive relations of concrete material (the horizontal part substitution for the downward part), such as Eqs. (13), (14) and Figure 4.

\[
\sigma = \sigma_0 \left[1 - \left(1 - \frac{\varepsilon}{\varepsilon_0}\right)^2\right] \quad 0 < \varepsilon \leq \varepsilon_0
\]

\[
\sigma = \sigma_0 \quad \varepsilon_0 < \varepsilon \leq \varepsilon_u
\]

\[
\varepsilon_0 = \frac{2\sigma_0}{E_0} \cdot f_c
\]

where \(\sigma_0 = 0.85 f_c\), \(\varepsilon_0 = \frac{2\sigma_0}{E_0}\), \(f_c\) is the concrete cylinder compressive strength. \(E_0\) is the initial modulus of elasticity of concrete.
The five-parameter model of William and Warnke is employed in the model. The failure surface of the model can readily be constructed by first obtaining the two meridians at $\theta = 0^\circ$, $\theta = 60^\circ$ from the two second-order parabolas (15) and (16). The surface is defined by an extension of Eq(17) to incorporate the dependence of $r_1, r_2$.

$$\frac{\tau_{mc}}{f_c} = a_0 + a_1 \frac{\sigma_m}{f_c} + a_2 \left(\frac{\sigma_m}{f_c}\right)^2 \quad \theta = 60$$

$$\frac{\tau_{mt}}{f_c} = b_0 + b_1 \frac{\sigma_m}{f_c} + b_2 \left(\frac{\sigma_m}{f_c}\right)^2 \quad \theta = 0$$

$$r(\theta) = \frac{2r_1 \left(r_2^2 - r_1^2\right) \cos \theta + r_2 \left(2r_1 - r_2\right) \sqrt{4\left(r_2^2 - r_1^2\right) \cos^2 \theta + 5r_1^2 - 4r_1 r_2}}{4\left(r_2^2 - r_1^2\right) \cos^2 \theta + \left(2r_1 - r_2\right)^2}$$

According to the characteristics of the shear connector test and relevant research materials, the Hognestad’s empirical formula is chosen to formulate the constitutive relations of concrete material (the horizontal part substitution for the downward part), such as Eqs. (13), (14) and Figure 4. According to the mechanical characteristics of the steel beams, stirrups and perforating rebars, the ideal elastoplastic models in this article are adopted for simulating the constitutive relations. The elastic modulus and yield stress of the girder is 210 GPa and 320 Mpa respectively. The elastic modulus and yield stress of the stirrups is 208 GPa and 400 MPa respectively. The perforating rebars’ elastic modulus and yield stress is the same as the value of the stirrups. The stud connectors used the three linear model, the elastic modulus, yield stress and limit stress is 208 GPa, 350 MPa and 480 MPa respectively. The materials of the steel beams, stirrups and shear connectors adopt Von-Mises yield criterion.

In the model, Solid 45 is adopted to simulate the steel beams, studs and perforating rebars. It has eight nodes, and each node has three translational degrees of freedom. Solid 45 also has the ability of the plasticity, creep, expansion, stress intensification and large deformation. Solid 65 is adopted to simulate the concrete, which based on Solid 45. It is designed for the development of concrete structure, so it can be originalistically used to simulate the strengthening of reinforcing steel bar of the concrete, the phenomenons of concrete cracking and crushing. Link 8 is adopted to simulate the stirrups. It is a kind of two nodes 3-D bar element, and each node has three degrees of freedom.

**The validation of finite element model.** Based on the push-out tests of φ19×125mm stud studied by Gattesco and Giuriani[6], which compared with the results of the established finite element model in this paper is shown in figure 5. In figure 5, the results of the analysis by the finite element method
are in good agreement with the tests when the load under 60 kN. The stud began to enter into the inelastic phase at the applied load of 75 kN in the experiment, but the finite element calculation results show that stud reached the plastic stage at the applied load of 90 kN. Through comparison, the relative deviation between the finite element value and test data is 16.6%. The stud ultimate bearing capacity is 106 kN measured by the test, the finite element result is 112 kN, the relative deviation is 5.35% through comparison. After reaching the limit load, the test results is slightly lower; the finite element result is basically identical. In general, the results of the experiment agree with that of the finite element method, which indicates that the finite element model can be used to calculate the shear bearing capacity and shear stiffness of the stud.

**Design of shear connectors.** According the above finite element model, the bearing capacity and shear stiffness of the stud used in test model can be calculating. The number of shear connectors can be obtained.

**Test Model Accuracy**

Three-dimensional finite element models of test model and original structure are used to investigate the accuracy of the test model. The results of stress measuring point of the test model and original bridge were shown in figure 6. Where Z represents the scale coordinate of original bridge in longitudinal direction and the original coordinate of the test model in longitudinal direction, the vertical axial in figure represents the normal stress of model and original structure. T represents the stress measure on top plate, B represents the stress measure on bottom plate. R represents the stress measure on original structure, M represents the stress measure on test model. The number represents the column number of stress measure.

By the contrast of the measuring data of the top and bottom plate, it can be found that there is little deviation between the test model and original structure, whether the top plate or the bottom plate. The deviation is within 10%. In general, the model of stress distribution regularity of the top and bottom plate is similar with the original structure.

**Summary**

According to the study on test model program of steel-concrete composite connection, the following conclusions can be made:
1. The test model program adopting the same similarity ratio can be used in investigating steel-concrete composite connection.
2. The stress of test model is similar to the original bridge. The test model can be used to analysis and reflect the stress of original bridge.
3. The bearing capacity and shear stiffness of the stud can be calculated through the finite element modeling.

References


