Nonlinear Analysis of Steel-Concrete Composite Deck Considering Interfacial Slip and Uplift

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ABSTRACT
Experiment plays an important role in studying the mechanical performance of structures in civil engineering. But it takes a lot of time and costs expensively. Numerical model is a good option to simulate the test results. It is also convenient to carry out parameter analysis. This paper introduced the entire process of a numerical simulation of steel-concrete composite deck test. The mechanism of interfacial behavior is analyzed. Simulation method of interface is introduced specifically. The results show that the proposed method of interfacial simulation is applicable. The results of simulation and test agree well with each other. The slip is nonlinear with load. It releases the interfacial connection and enlarges the deflection of composite deck. The uplift is quite small compared with slip so that it can be neglected when evaluating the structure behavior of composite deck.

KEYWORDS: Steel-concrete composite deck, Numerical simulation, Slip, Uplift

1 INTRODUCTION
Steel-concrete composite deck is being used more and more in bridge engineering (Fan and Nie, 2006). It combines the steel girder with the concrete slab by shear connectors. It works as a whole and has good economical and mechanical performance (Aldeen et al., 2011). With the increase of load, slip and uplift will occur on the interface which would diminish the bearing capacity and enlarge the deformation of structures (SakrandSakla, 2008). It would also cause nonlinear response of composite structures (SotyandShima, 2013). It is valuable and necessary to measure the interfacial states of composite structures in order to evaluate the structure performance (Chen and Shi, 2011). However, the recent research on steel-concrete composite deck concentrated on the experimental study. The numerical simulation is only a supplementary method (Yang et al., 2009).

The simulation of interface is the most important and the most complex point part in the numerical simulation of composite structures (Yang et al., 2006). The interfacial slip along the beam direction is usually considered as the key factor of simulation (Nie and Wang, 2012). The transverse slip is either neglected (Xu et al., 2012) or treated linearly (Nguyen et al., 2001). Spring elements are usually used to connect the concrete slab and steel girder (Ranzi et al., 2006). The effect of interfacial friction and contact cohesion are integrated into the constitutive relationship of spring element (Kwak and Seo, 2002).

This paper introduced the entire process of numerical simulation of steel-concrete composite deck test including element types, constitutive relationship, interfacial simulation, boundary condition and convergence condition. The composite deck was designed based on a practical engineering. Test results were presented by Zhan et al. (2014). Interfacial friction, contact cohesion and resistance of shear connector are analyzed and simulated, respectively. Results of deflection, slip, uplift and crack are illustrated and compared.

2 EXPERIMENTAL PROGRAM
2.1 Design of steel-concrete composite deck
The test model of steel-concrete composite deck is shown in Figure 1. The test specimen is 5000mm long, 2400mm wide and 1212mm high. Steel fiber reinforced concrete is used to cast the concrete slab. The concrete slab is 120mm thick at the edge and 200mm thick in the middle. It is cast on an 8mm thick steel plate. The

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steel girder is in H-shape section which is 600mm in width and 1004mm in height. The thicknesses of flange and web are 16mm and 20mm, respectively.

Concrete slab is connected to steel plates by shear connectors including studs (Φ22mm×160mm) and perfobond strips (PBL, 10mm in thickness). The arrangement of shear connectors is shown in Figure 2. Studs are placed at a spacing of 200mm transverse and 400mm longitudinal, respectively. PBLs are at a spacing of 400mm longitudinal. Crack sensors, slip sensors and uplift sensors were arranged as shown in Figure 2.

2.2 Loading procedure
There were two phases of loading program as shown in Figure 3. The loading-unloading-reloading process was considered. In phase I, load was gradually increased to 844kN and then decreased to 0kN. In phase II, load remained increasing until the failure of structure.

3 NUMERICAL SIMULATION
The finite element software ANSYS was introduced to simulate the behavior of steel-concrete composite deck. The FE model is demonstrated in Figure 4. There are 3024 elements including solid elements, shell elements, spring elements, contact elements and target elements.
3.1 Simulation of interface

The interfacial behavior of steel-concrete composite deck could be summarized in three types. When the interfacial shear force is small, there is no slip between concrete slab and steel plate. The resistance of shear connectors and the interfacial cohesion are the main factors to influence the interfacial performance as shown in Figure 5(a). When slip occurs without uplift, the interfacial cohesion has been released and friction takes its place. The resistance of shear connectors and the friction on the interface contribute much to the interfacial performance as shown in Figure 5(b). Shear connectors resist both slip and uplift on the interface if concrete slab separates from steel plate as shown in Figure 5(c). Other effects do not function any more.

![Finite element model](image)

**Figure 4.** Finite element model

![Schematic diagram of interfacial behavior of composite deck](image)

**Figure 5.** Schematic diagram of interfacial behavior of composite deck

Push-out test method is usually used to evaluate the interfacial performance. A typical push-out test result is shown in Figure 6, where $P$ is the force of push-out test, $s$ is the slip at interface. Due to the interfacial cohesion, there is no slip until the force reaches point A. No lateral force was applied on the push-out specimen thus the interfacial friction can be neglected. The resistance of shear connectors plays an important role on the force-slip curve. Segment AB and BC represent the elastic and strengthening period of shear connectors. At point C, the shear connectors yield. Push-out force remains, but the slip develops significantly in segment CD. The weakness of shear connectors occurs after point D which induces the descent of force-slip curve.

![Typical result of push-out test](image)

**Figure 6.** Typical result of push-out test

Three types of elements were introduced to simulate the interfacial interaction. A spring element provides a constraint between two nodes which represents the resistance of shear connectors as shown in Figure 5. One node
is on the concrete slab and the other on the steel plate. The constitutive relationship of spring element is that of the shear connectors, which means it can be derived by the push-out test results. Contact element and target element are used in pairs to represent the two surfaces of the interface. Contact cohesion and friction coefficient are two parameters of elements to simulate the interfacial cohesion (Figure 5(a)) and friction (Figure 5(b)), respectively. Details of elements are shown in Figure 7.

![Figure 7. Details of interfacial elements](image)

### 3.2 Element type

1. **Solid65 element**

   FE element Solid65 is defined by 8 nodes having 3 degrees of freedom in translations at each node. It is usually used to simulate the reinforced concrete in three dimensions. It is capable of cracking in tension and crushing in compression. To consider the effect of reinforcement, real constant by defining the ratio of reinforcement is introduced to the element. In addition, 10% of PBL connectors were considered as reinforcement in z direction when calculating the bearing capacity of composite deck (Xu, 2013). Concrete failure criterion was defined by the element input parameters in “Solid65 concrete material data”. Solid65 elements were used to simulate the steel fiber reinforced concrete slab and the loading plates (shown in Figure 4).

2. **Shell63 element**

   Element Shell63 is defined by 4 nodes having 6 degrees of freedom in translations and rotations at each node. The element has bending and membrane capabilities. It allows stress stiffening and large deflection. Shell63 is used to simulate the steel plates, steel girder and rib stiffeners, respectively (shown in Figure 4). The thickness of shell is defined by the real constant of element.

3. **Combin39 element**

   Nonlinear spring element Combin39 is a unidirectional element with 2 nodes. Each node has 3 degrees of freedom in translations. The Combin39 element connected two nodes like a spring. The constitutive relationship is defined by generalized force-deflection curve. Combin39 elements were applied at the places of studs and PBLs to represent the resistance of shear connectors (shown in Figure 8).

![Figure 8. Demonstration of interfacial simulation](image)

4. **Conta173 element and Targe170 element**

   Conta173 element is formed in coordination with Targe170 element. They are located on the surface of solid or shell element so that it has the same geometric characteristics. Contact and slip are the two main activities of interface which are defined by element parameters. They work together according to the definition of real constants.

   The arrangement of spring elements and contact elements is shown in Figure 8. Spring elements were placed coincided with shear connectors. Contact elements were on the top surface of steel plates and steel girder. Target elements were on the entire bottom surface of concrete slab.
3.3 Constitutive relationship

(1) Steel

The constitutive relationship of steel is the bilinear isotropic hardening model as shown in Figure 9, where $f_y$ and $\varepsilon_y$ are the yield stress and yield strain of steel, respectively. Tangent modulus was set to 1% of elastic modulus in the simulation. The constitutive relationship is defined according to material property test results as shown in Table 1.

![Stress-strain curve for steel](image)

**Figure 9. Stress-strain curve for steel**

### Table 1. Summary of steel properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness(mm)</th>
<th>$f_y$(MPa)</th>
<th>$f_u$(MPa)</th>
<th>$E_s$(GPa)</th>
<th>$\mu_s$</th>
<th>$\delta_s$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper flange</td>
<td>16</td>
<td>281.99</td>
<td>431.80</td>
<td>190</td>
<td>0.26</td>
<td>33.90</td>
</tr>
<tr>
<td>Lower flange</td>
<td>20</td>
<td>263.89</td>
<td>433.36</td>
<td>198</td>
<td>0.27</td>
<td>31.80</td>
</tr>
<tr>
<td>Web</td>
<td>16</td>
<td>281.99</td>
<td>431.80</td>
<td>190</td>
<td>0.26</td>
<td>33.90</td>
</tr>
<tr>
<td>Steel plate</td>
<td>8</td>
<td>266.41</td>
<td>457.73</td>
<td>195</td>
<td>0.27</td>
<td>29.97</td>
</tr>
</tbody>
</table>

(2) Concrete

The constitutive relationship of concrete was based on Hongnestad model (Hongnestad, 1955) which is shown in Figure 10. $\sigma_0$ is the compressive strength of concrete. $\varepsilon_0$ and $\varepsilon_u$ are set to 0.002 and 0.0038, respectively. Equations 1 and 2 are expressions of Hongnestad model:

$$
\sigma = \begin{cases} 
2 \frac{\varepsilon}{\varepsilon_0} - \left( \frac{\varepsilon}{\varepsilon_0} \right)^2 \cdot \sigma_0 & 0 \leq \varepsilon \leq \varepsilon_0 \\
1 - 0.15 \frac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \cdot \sigma_0 & \varepsilon_0 \leq \varepsilon \leq \varepsilon_u 
\end{cases}
$$

The material property of concrete is shown in Table 2.

### Table 2. Summary of concrete strength

<table>
<thead>
<tr>
<th>$f_{cu}$(MPa)</th>
<th>$f_t$(MPa)</th>
<th>$E_c$(GPa)</th>
<th>$\mu_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.95</td>
<td>3.67</td>
<td>30.2</td>
<td>0.23</td>
</tr>
</tbody>
</table>

(3) Spring element

The constitutive relationship of spring element is a force-slip curve. The longitudinal and transverse spring element is defined as shown in Figure 11. The slip of the curve is the interfacial slip of push-out test. The force of the curve is the push-out force divided by the number of springs at the interface. The force should be modified correspondingly if the mesh size was changed. The descent segment of force-slip curve was neglected.
The vertical spring element is defined as an elastic spring to resist interfacial uplift because the resistance to uplift is very strong. The stiffness of vertical spring is defined as \( \frac{EA}{l} \), where \( E \) is the elastic modulus of steel, \( A \) is the section area of shear connector, \( l \) is the height of shear connector.

4 Contact element and target element

Friction coefficient and contact cohesion are the two most important real constants for structural analysis. The two constants were determined by push-out tests. Friction coefficient (\( \mu \)) was set to 0.4. Contact cohesion (COHE) was set to 0.5 MPa in Phase I. During the loading process in Phase I, the contact cohesion was released little by little. Therefore COHE was set to 0 MPa in Phase II.

3.4 Boundary condition and loading procedure

It was found by the test that the deformation of the support solids is so small that could be neglected. Therefore the support solids were not formed in the simulation. Boundary conditions were applied directly at the extended steel girders with all the degrees of freedom constrained as shown in Figure 4. Surface pressure was applied on the loading plates. The load increment was refined compared with the experimental procedure. The convergence condition of finite element analysis was displacement controlled with a tolerance of 2%.

4 COMPARISONS BETWEEN EXPERIMENTAL RESULTS AND NUMERICAL SIMULATIONS

4.1 Deflection

The Comparison on load-deflection relation is shown in Figure 12. The analytical result is in good agreement with the test. Numerical simulation stopped when the model was no longer convergent. No abrupt failure of structure occurred.

4.2 Crack

Crack result is the strain along \( z \) direction on the top surface of concrete slab. The comparison is shown in Figure 13. The generation of crack was indicated by the abrupt increase of strain in both simulation and test. The cracking load of simulation was 77kN which agreed well with the test result (79kN).

4.3 Slip

The comparison of slip between test and simulation is shown in Figure 14. The numerical model was the simulation of reloading process of Phase II. The contact cohesion (COHE) was 0 during the simulation. Compared to the test result of Phase I, the release of contact cohesion enlarged the initial slip. But the results matched well in the latter loading process. After 850kN, the slip in the simulation was greater than that in Phase II because the contact cohesion through the entire interface was neglected in the simulation.
4.4 Uplift

The uplift-load curves shown in Figure 15 were not smooth. It indicated that the shear connectors played an important role in resisting the separation of interface. The process of uplift was illustrated in Figure 16. When stud-1 could not resist the separation force $f$, the uplift sensor would detect an intense signal of uplift. The force $f$ kept increasing, but the uplift was restricted by stud-2 until $f$ was strong enough to destruct the resistance of stud-2. The uplift sensor would then detect another intense signal. The process repeated and the uplift-load curve went like a zigzag line.

![Figure 15. Uplift-load relation of sensor X3 and X4](image1.png)

![Figure 16. Process of uplift](image2.png)

5 CONCLUSIONS

This paper introduced a numerical analysis on the nonlinear performance of steel-concrete composite deck. The interfacial simulation was introduced specifically. Results of deflection, concrete crack, interfacial slip and uplift were analyzed. Conclusions are summarized as follows:

The interfacial behavior is mainly determined by three factors: friction, contact cohesion and resistance of shear connectors. By introducing contact element and target element into the finite element models, the friction and contact cohesion are considered respectively. The resistance of shear connectors is simulated by spring element. The constitutive relationships are determined mainly by push-out test.

The interfacial slip shows significant nonlinearity. It has great influence to the structure behavior of composite structures. The stiffness of spring element to resist uplift is excessively high. Compared to slip, the magnitude of uplift is so small that can be neglected when evaluating the structure behavior.

The results of simulation and test agree well with each other. The introduced method for simulation of steel-concrete composite deck is reasonable and can be proposed to the other forms of composite structures. Further research is still required to simulate the interfacial behavior of the loading-unloading-reloading process.

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