Study on the Basic Performance of Steel-UHPC Lightweight Composite Structures for Long-span Bridges

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ABSTRACT

For the bridges of long-span continuous system and flexible system, the traditional steel-concrete composite girders have two problems. First, because the ordinary concrete has a low tensile strength, the ordinary concrete is easy to crack in the negative-moment region. Second, due to the heavy self-weight, the traditional steel-concrete composite girders are not economical for long-span bridges. In order to solve the above problems, steel-UHPC (Ultra-high Performance Concrete) lightweight composite girder bridges were proposed in this paper. The writer uses a thin UHPC bridge deck to replace the thick concrete bridge deck in the traditional composite girder, which can reduce its weight by about 35% and ensure its high cracking strength and superior durability at the same time. This paper is mainly to introduce the economic and flexural performance of two types of UHPC bridge decks, which can provide a help for the construction of long-span composite girder bridges.
KEYWORDS: bridge engineering; ultra-high performance concrete; steel-UHPC composite bridge; economic performance; flexural performance

1 INTRODUCTION

Because steel structure bridges have many advantages such as light weight, high strength, and environment friendly, in July 2016, the Ministry of Chinese Transport issued Guiding Opinions on Promoting the Use of Steel Structures in Highway Bridge Construction [2016 No. 115]. It will promote the highway construction and the quality of highway bridges. Steel structure bridges usually include steel girder bridges and steel-concrete composite girder bridges. Up to June 2017, construction of long-span bridges with main span over 400 m counts on suspension bridges and cable-stayed bridges mostly. Among the bridges with main span over 400 m, there are about 57 suspension bridges and 100 cable-stayed bridges constructed or in construction in China.

Steel girders usually have the priority in the construction of long-span bridges due to its light weight. In addition, steel girders use the orthotropic steel decks (OSD) as its bridge decks. However, OSD and its pavement are easily to have fatigue cracks and easily to damage\(^1\)-\(^2\). A novel steel-UHPC (Ultra-high Performance Concrete) lightweight composite bridge deck was proposed to replace the traditional OSD and asphalt pavement, which can solve the above problem of traditional steel girders effectively\(^3\).

Compared with steel girders, not only can steel-concrete composite girders take advantage of the high compressive strength of ordinary concrete, but also can take advantage of the high tensile strength of steel. Traditional steel-concrete composite girders use thick ordinary concrete bridge decks to replace OSDs, which can increase more flexural stiffness of both the girders and bridge decks. More flexural stiffness can reduce the vertical displacement and the flexural stress of the bridge deck under the vehicle load, which can avoid OSD to have fatigue cracks. Although the cost of ordinary concrete bridge deck is much lower than that of OSD, the weight of the thick ordinary concrete bridge deck is much heavier than that of OSD, which brings a great difficulty to the design of long-span steel-concrete composite girder bridges. In addition, due to the bad tensile performance of the ordinary concrete, cracks happen easily to ordinary concrete bridge deck of the long-span continuous and flexible steel-concrete composite girder bridges in the negative bending moment zones. These measures below are usually adopted to avoid cracking and to control the crack width in the actual engineering projects. Such as using prestressed reinforcement, connecting the concrete slabs with the steel girder partially, lifting the middle supports, specifying the minimum reinforcement ratio of the concrete slab, etc. However, these measures not only increase the difficulty in bridge construction, but also bring new problems on prestress loss caused by the shrinkage and creep of the ordinary concrete. Thus, steel-concrete composite girders are hardly applied to long-span bridges with main span over 600 m. For continuous composite beam bridges, Brozzetti\(^4\) investigated composite girder bridges in France and then found that composite girder bridges with main span of 30 m–110 m have a good economic advantage. When the main span of a composite girder is more than 110 m, building continuous steel-concrete composite beam bridges are unreasonable due to the increasing negative bending moment. For cable-stayed composite girder bridges, the increasing weight of the main girder will result in increasing cable tension and increasing the pressure of bridge deck. Eventually, building cable-stayed steel-concrete composite girder bridges are unreasonable due to the overlarge pressure of bridge deck. Svensson\(^5\) found that the maximum economic span of cable-stayed composite girder bridge is 600 m. For composite girder suspension bridges, the stiffening girder is not the first force-bearing system. The self-weight is completely borne by the main cable system. Thus, building large weight composite girder suspension bridges are unreasonable.

Because of the excellent properties of UHPC, the problems of traditional ordinary concrete bridge decks of steel-concrete composite girders can be solved effectively by utilizing novel UHPC bridge decks. UHPC, as the most innovative cementitious composite materials in recent 30 years, is composed of different particle sizes which form the most closely packed UHPC with the optimum ratio to make the defects inside (pores and micro cracks) to be minimum. Therefore, UHPC exhibits high strengths and excellent durability. In addition, the fine steel fiber mixed in the UHPC makes it to
show the characteristics of good toughness and ductility\textsuperscript{[7]}.
Research on the material properties of UHPC indicated that its compressive strength can exceed 150 MPa, and its flexural tensile strength is about ten times higher than that of ordinary concrete, the fracture toughness is approximately 200 times higher than that of ordinary concrete, and the design life of UHPC structures could be over 200 years\textsuperscript{[8]}.

In order to solve the problems of traditional steel-concrete composite girders, UHPC bridge deck structure is proposed to replace the traditional ordinary concrete bridge deck in this paper. Based on its ultra-high mechanical properties and high durability, novel UHPC bridge deck structures are designed for long-span steel-UHPC composite girder bridges. The basic performance of UHPC bridge deck in steel-UHPC lightweight composite girder was studied in this paper, including the economic performance and the flexural performance.

2 STRUCTURE CONCEPT

Utilizing ultra-high mechanical properties and durability of UHPC, the bridge decks of composite girders could be made thin and lightweight. The thin and lightweight UHPC bridge deck not only can improve its flexural performance but also can reduce much weight of the whole composite girder\textsuperscript{[9]}. The steel-UHPC lightweight composite girder includes two parts: the upper UHPC bridge deck and the under-steel structure. The types of the upper UHPC bridge deck include two kinds: the rectangular bridge deck and the waffle deck panel with low ribs. And the types of the under-steel structures include three kinds: plate girder with ribs, U-type box girder and truss girder. The novel steel-UHPC lightweight composite girder structures were shown in Figure 1.

![Figure 1: Novel Steel-UHPC Lightweight Composite Girder Structures](image)

For long-span bridges, the average thickness of ordinary concrete bridge decks in traditional steel-concrete composite girders is more than 28 cm, which lead that the self-weight of common concrete bridge decks can account for more than 70\% of the self-weight of the whole steel-concrete composite girders. While the average thickness of the UHPC bridge decks can be reduced to 13–17 cm, the weights of composite girders can be reduced by 30–40\%. The thickness of rectangular UHPC bridge deck is about 16–17 cm. In order to reduce the weight of UHPC bridge deck further and to increase the stiffness of the UHPC bridge deck, another type of UHPC bridge deck, the UHPC waffle deck panel with low ribs, was proposed in this paper. The average thickness of waffle deck panel can be reduced to 13–15 cm\textsuperscript{[10]}. Because of the high tensile strength of UHPC, the risk of cracking and the use of prestressed reinforcement will be greatly reduced.
The steel-UHPC lightweight composite girder bridge has many advantages such as ultra-high strength, light weight and low risk of cracking, which could solve the radical problems of the traditional steel-concrete composite girders. For the traditional steel-concrete composite girder cable-stayed bridges, the economical and rational span is about 400-600 m. However, the steel-UHPC lightweight composite girder can extend that economical and rational span to 1000 m[9], which will broaden the application of the composite girders for long-span cable-stayed bridges widely.

3 ECONOMIC COMPARISON

Because the under-steel structures of the steel-UHPC lightweight composite girders are similar to the steel girders and traditional steel-concrete composite girders, the comparisons of the self-weight and economic performance are mainly introduced in this paper, respectively. Based on the background of the design of one practical long-span bridge, three different typical bridge deck systems were picked up to compare each self-weight and corresponding economic performance. And the results were shown in Table 1. Three different typical bridge deck systems are orthotropic steel bridge deck (OSD)+8 cm epoxy asphalt concrete, average 15 cm UHPC bridge deck+8 cm common asphalt concrete and average 28 cm ordinary concrete bridge deck+10 cm common asphalt concrete. The orthotropic steel bridge deck includes 16 mm steel slab+8 mm U-shaped stiffeners. The service life of all the asphalt-concrete pavements is assumed to be 10 years. The initial and whole-life construction costs include material cost, construction cost and processing cost. The whole-life time for long-span bridges is assumed to be 100 years.

Table 1 Comparisons of the Self-weight and Initial and Whole-life Construction Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>OSD</th>
<th>UHPC Bridge Deck</th>
<th>Ordinary Concrete Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>16mm steel slab+8cm epoxy asphalt concrete</td>
<td>15cm UHPC bridge deck+8cm common asphalt concrete</td>
<td>28cm ordinary concrete bridge deck+10cm common asphalt concrete</td>
</tr>
<tr>
<td>Weight or Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel (kN/m²)</td>
<td>1.25</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>U-shaped stiffener (kN/m²)</td>
<td>0.76</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>UHPC (kN/m²)</td>
<td>—</td>
<td>4.05</td>
<td>—</td>
</tr>
<tr>
<td>Ordinary Concrete (kN/m²)</td>
<td>—</td>
<td>—</td>
<td>7.0</td>
</tr>
<tr>
<td>Asphalt Concrete (kN/m²)</td>
<td>1.92</td>
<td>1.92</td>
<td>2.4</td>
</tr>
<tr>
<td>Total (kN/m²)</td>
<td>3.93</td>
<td>5.97</td>
<td>9.4</td>
</tr>
<tr>
<td>Initial Cost (yuan/m²)</td>
<td>3611</td>
<td>1596</td>
<td>1044</td>
</tr>
<tr>
<td>Whole-life Cost (yuan/m²)</td>
<td>16211</td>
<td>2460</td>
<td>2124</td>
</tr>
</tbody>
</table>

Note: The data in the table is from the reference[9].

The volumetric weight of the ordinary concrete (including reinforcement) is 25 kN·m⁻³, the initial cost of the ordinary concrete (including reinforcement) is RMB 3,300 yuan·m⁻³. The volumetric weight of the UHPC (including reinforcement) is 27 kN·m⁻³, the initial cost of the ordinary concrete (including reinforcement) is RMB 10,000 yuan·m⁻³. The volumetric weight of the epoxy and ordinary asphalt concrete is 24 kN·m⁻³, the initial cost of the epoxy asphalt concrete is RMB 17,500 yuan·m⁻³, the initial cost of the common asphalt concrete is RMB 1,200 yuan·m⁻³. The volumetric weight of steel is 78 kN·m⁻³, the initial cost of the ordinary concrete (including reinforcement) is RMB 11,000 yuan·t⁻¹.

From the weights of three different bridge deck systems in Table 1, we can found that the weight of UHPC deck system is 5.97 kN/m², which is about 63.5% of that of the traditional ordinary concrete bridge deck. But it is about 152% of the self-weight of the orthotropic steel bridge deck. Further, it shows that the self-weight of traditional steel-concrete composite girder is too large to be applied in long-span bridges with main span over 600 m. As in virtue of the weight of UHPC bridge deck is much reduced, steel-UHPC composite girders can be easily applicable to long-span bridges with main span over 600 m.
In terms of the initial cost shown in Table 1, the initial cost of 15 cm UHPC bridge deck is RMB 1,596 yuan/m², which is about 153% of that of the traditional ordinary concrete bridge deck. But it is about 44% of the initial cost of the orthotropic steel bridge deck. Further, the whole-life cost of 15 cm UHPC bridge deck is RMB 2,460 yuan/m², which is about 116% of that of the traditional ordinary concrete bridge deck. But it is about 15% of the whole-life cost of the orthotropic steel bridge deck. Therefore, it can be concluded that the steel-UHPC lightweight composite girders have a good economic performance, especially in the whole-life cost, for long-span bridges with main span over 600 m.

In addition, UHPC bridge decks have low risk of cracking and involve less or no prestressed reinforcement, which will bring more unpredictable economic advantages. In summary, the steel-UHPC lightweight composite girder structures studied in this paper possess the potential ability to break through the difficulties of building traditional long-span steel-concrete composite girders with main span over 600 m.

4 FLEXURAL PERFORMANCE OF THE UHPC BRIDGE DECK

Under the vehicle load, the underneath of bridge deck will suffer tensile stress in the mid-span positive-moment region. In the continuous-system bridges, the upper edge of bridge deck will also suffer tensile stress in the negative-moment region. In order to study the flexural performances of the lightweight UHPC bridge decks, two types of UHPC bridge deck were made. One type is the average 14 cm-thickness UHPC waffle bridge deck with low ribs, another type is 17 cm-thickness UHPC rectangular bridge deck. And the corresponding four-point bending tests were conducted to compare the their flexural performance.

4.1 Designs of Components

4.1.1 the Test Component of the UHPC Waffle Bridge Deck

As shown in Figure 2(a), for the test component of the average 14 cm-thickness UHPC waffle bridge deck with low ribs, the total length, the width, the height and the thickness of flange slab are 3700 mm, 700 mm, 220 mm and 80 mm, respectively. The calculated span of the test component is 3500 mm (the spacing between two diaphragms). The test component was made of UHPC and rebars. The UHPC contains hooked steel fiber (the volume is 2.5%, the diameter and length are 0.2 mm and 13 mm, respectively). The grade of rebars was HRB400 whose yield strength was 400 MPa according to Chinese standard. The thickness of concrete protective cover is 20 mm. The location of rebars in the test component (including upper rebars, underneath rebars, lateral rebars and stirrups) is shown in Figure 2(b). The numbers, diagrams and spacings of the rebars are shown in Table 2.

Table 2 Parameters of the Reinforcement

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Number</th>
<th>Diagram (mm)</th>
<th>Spacing (cm)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper rebars</td>
<td>N1</td>
<td>16</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>underneath rebars</td>
<td>N1b</td>
<td>20</td>
<td>11.4</td>
<td>3</td>
</tr>
<tr>
<td>lateral rebars</td>
<td>N2</td>
<td>12</td>
<td>10</td>
<td>39</td>
</tr>
<tr>
<td>stirrups</td>
<td>N3</td>
<td>6</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>

4.1.2 the Test Component of UHPC Rectangular Bridge Deck
As shown in Figure 3, for the 17cm-thickness UHPC rectangular bridge deck, the length and width of the test component were 1500 mm and 350 mm, respectively. The thickness of the test component was 170 mm and the calculated span of the test component is 1300 mm. The UHPC contains hooked steel fiber (the volume is 2.5%, the diameter and length are 0.2 mm and 13 mm, respectively). The longitudinal and transverse diameters of the rebars are 18 mm and 12 mm, respectively. The grade of rebars were HRB400. And the thickness of UHPC protective cover is 20 mm. The location of rebars in the test component (including upper rebars, underneath rebars and lateral rebars) is shown in Figure 3.

![Figure 3: Test Component of the UHPC Rectangular Bridge Deck (units: mm)](image)

### 4.2 Bending Test

Four-point bending tests carried out to determine the bending stiffness and the load-bearing capacity of two type components. A 500-kN capacity hydraulic jack was placed at the center of the distributive girder and then distributed the load onto the top surface of the components. The pins and roller were greased to minimize friction and gave free rotation and horizontal translation, as required. The components were tested until the components lost carrying capacity. The load on the components were measured by the force sensor. Figure 4(a) shows the test setup of the positive-moment bending test of the UHPC waffle bridge deck. And Figure 4(b) shows the test setup of the negative-moment bending test of the UHPC waffle bridge deck. The bending test setup of the UHPC rectangular bridge deck is shown in Figure 5.

![Figure 4: the Bending Test Setup of the UHPC Waffle Bridge Deck (units: mm)](image)

![Figure 5: the Bending Test Setup of the UHPC Rectangular Bridge Deck (units: mm)](image)

### 4.3 Comparison of the Test Results

Crack resistance is an important index to evaluate the flexural performance of the bridge deck and is also a major design index for serviceability limit state of bridge deck. Rafiee[11] studied and proved that the cracks with width less than 0.05 mm have no negative effect on the durability of UHPC. Therefore, when the maximum crack width of the UHPC reaches 0.05 mm, the corresponding
nominal tensile stress of the UHPC is determined as the cracking strength of the UHPC structure in this paper. Generally speaking, the bridge decks of composite girders in long-span cable-stayed bridges will suffer tensile stress of 5~7 MPa under the frequent combination effect of various loads. From the bending test above, this paper summarized the nominal tensile stresses of the UHPC in Table 3 when the maximum crack widths reached 0.05 mm and 0.06 mm, respectively. The test results proved that the flexural performances of two types of UHPC bridge deck meet the engineering requirements.

<table>
<thead>
<tr>
<th>Type</th>
<th>Positive Moment Waffle Component</th>
<th>Negative Moment Waffle Component</th>
<th>Rectangular Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{w,0.05}$ (MPa)</td>
<td>19.4</td>
<td>13.8</td>
<td>23.2</td>
</tr>
<tr>
<td>$\sigma_{w,0.06}$ (MPa)</td>
<td>34.1</td>
<td>18.1</td>
<td>30.9</td>
</tr>
</tbody>
</table>

From the results in Table 3, for the average 14 cm-thickness UHPC waffle bridge deck, the cracking strengths of positive-moment and negative-moment were 19.4 MPa and 13.8 MPa, respectively. While the maximum crack widths reached 0.06 mm, the nominal tensile stresses of the UHPC were 34.1 MPa and 18.1 MPa, respectively. For the 17 cm-thickness UHPC rectangular bridge deck, the cracking strength was 23.2 MPa. While the maximum crack width reached 0.06 mm, the nominal tensile stress of the UHPC was 30.9 MPa. It is proved that the steel fiber in the UHPC can suppress the development of cracking effectively.

5 CONCLUSIONS

The flexural performance of the concrete bridge deck can be well improved by utilizing the novel lightweight UHPC bridge deck to replace the traditional ordinary concrete bridge deck in steel-concrete composite girder. In addition, the weight of ordinary concrete bridge deck can be reduced by 40~50%. And the weight of steel-concrete composite girder can be reduced by 30~40%. The novel steel-UHPC lightweight composite girders could solve the radical problems of the traditional steel-concrete composite girders. And they can broad the application of the composite girder for long-span bridges widely.

As for the economic performance, the self-weight of the UHPC deck system is about 152% of that of the orthotropic steel bridge deck system. But the UHPC bridge deck system is much cheaper than the orthotropic steel bridge deck system. The initial cost of 15 cm-thickness UHPC bridge deck system is about 44% of that of the orthotropic steel bridge deck system. Further, the whole-life cost of 15 cm-thickness UHPC bridge deck system is about 15% of that of the orthotropic steel bridge deck system. In addition, UHPC bridge decks have low risk of cracking and involve less or no prestressed reinforcement, which will bring more unpredictable economic advantages.

For the flexural performance, the cracking strengths of positive-moment and negative-moment of the average 14 cm-thickness UHPC waffle bridge decks were 19.4 MPa and 13.8 MPa, respectively. The cracking strength of the 17 cm-thickness UHPC rectangular bridge deck was 23.2 MPa. It is proved that the steel fiber in the UHPC can suppress the development of cracking effectively.

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