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Field measurement and practical design of a lightweight composite bridge deck

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ABSTRACT

Ultrahigh-performance concrete (UHPC) layers play an important role in steel-UHPC lightweight composite bridge decks. To characterize the contribution of the UHPC layer to these decks, field measurements were conducted, and the strain responses of various detail categories were measured for orthotropic steel decks with and without UHPC layers. The results show that the UHPC layer influences the stress range of the various detail categories significantly. ANSYS software was also applied to model the lightweight composite bridge deck, and a transient analysis was performed to investigate the influence of the vehicle speeds. Finally, the influence surfaces of the detail categories were introduced to determine the variation of the stress range, and a simple method was proposed to design the UHPC layer.

1. Introduction

Due to its light weight, the orthotropic steel deck has been widely applied in long-span bridges [1]. Modern steel bridges are subjected to increasing traffic loads. As a result, premature fatigue cracking may occur in some orthotropic steel decks, leading to severe serviceability problems for steel bridges [2]. In fact, the fatigue phenomenon has become one of the most severe threats to orthotropic steel bridge decks. Therefore, multiple studies have focused on the fatigue characteristics of such decks [3-7].

The lightweight composite bridge deck was recently designed to improve the fatigue performance of a steel bridge [8]. For this type of deck, an ultrahigh-performance concrete (UHPC) layer is laid onto the orthotropic steel deck. Therefore, the stress range of this deck is expected to decrease significantly. Shao and his co-workers investigated the role of the UHPC layer and the fatigue characteristics of the lightweight composite bridge deck [9-11]. Although these studies are of importance for the development of the lightweight composite bridge deck, the contribution of the UHPC layer to various detail categories remains unclear in the actual situation because of the challenge of simulating the actual situation of the wheel load according to the laboratory conditions. Therefore, the effects of the UHPC layer must be verified by field measurement results.

The UHPC layer substantially increases the stiffness of the lightweight composite bridge deck [8]. Therefore, the fatigue life of the lightweight composite bridge deck is expected to be much longer than that of the orthotropic steel deck. In practice, the UHPC layer is designed with a thickness of 35–60 mm to extend the fatigue life of the lightweight composite bridge deck [12]. The determination of the thickness of the UHPC layer relies on the limited engineering application and relatively little engineering experience, furthermore, no theoretical background exists that can be applied to support this determination. The thickness of the UHPC layer according to engineering experience cannot ensure an adequate fatigue life of the lightweight composite bridge deck. Therefore, it is important to propose a corresponding design method for the UHPC layer to satisfy the special requirement of fatigue-resistant design.

In this field study, the Fengxi Bridge was chosen as the subject to illustrate the effects of applying a UHPC layer on an orthotropic steel deck. Moreover, a three-dimensional finite element model was developed to verify the field measurement results and to examine the influence of the vehicle speeds. Finally, design curves were obtained to design the UHPC layer of the lightweight composite bridge deck. The major contributions of this study are twofold: (a) field measurements were conducted to reveal the effects of the

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UHPC layer on the stress range of various detail categories of the lightweight composite bridge deck, and (b) a new design method was proposed to determine the thickness of the UHPC layer.

2. Bridge description

In this study, the Fengxi Bridge was selected to experimentally verify the effectiveness of the UHPC layer. This bridge, located in Hunan Province, China, is a self-anchored suspension bridge. Fig. 1 (a) shows the elevation view of the suspension bridge, which has a total length of 570 m. Moreover, two main cables with a sag ratio of 1/5 are designed to support the deck via 32 pairs of suspenders, and the deck includes six traffic lanes and two footpaths. The main span of 300 m is composed of a steel box girder with a height of 3.5 m and a width of 32 m; the steel deck plate is 14 mm thick and is stiffened with 8 mm trapezoidal ribs spaced at 600 mm. The diaphragms where hangers are anchored have a thickness of 16 mm, and the other diaphragms have a thickness of 12 mm; the diaphragms are spaced at 3000 mm. Fig. 1 (b) shows the half-cross-section of the steel box girder. To enhance the stiffness of the steel box girder and improve the fatigue characteristics of the orthotropic steel deck, the UHPC layer is designed with a thickness of 50 mm to construct the lightweight composite deck, as shown in Fig. 1 (c). Furthermore, reinforcing bars with a yield strength of 400 MPa are laid to improve the strength of the UHPC layer (see Fig. 1 (c)).

3. Instrumentation and loading procedure

The stress ranges generally dominate the fatigue assessment of the structure. Therefore, the instrumented sections where the stress ranges are higher are important when conducting field measurements. To determine these sections, before the field measurements were conducted, a global beam element model of the Fengxi Bridge was developed in Midas Civil, and a transient analysis of the bridge as affected by a moving vehicle was performed. The numerical results show that the maximum stress range occurs in the #18 segment. Therefore, the instrumented sections were chosen at 1/3 of the span of the Fengxi Bridge (#18 segment, see Fig. 1) to measure the strain response of the orthotropic steel deck with or without the UHPC layer. The measurements include the strain response of the orthotropic steel deck at various locations, and the response of the orthotropic steel deck was measured using bondable uniaxial strain gauges. Fig. 2 shows the instrumented sections and the locations of the strain gauges. Overall, 68 strain gauges were installed on the deck, rib, and diaphragm, and they were all located in the neighbourhood of the #3 diaphragm (see Fig. 2). However, only the response of three important detail categories, i.e., the rib-to-deck weld, the rib splice weld, and the cope hole, are presented for brevity. The three selected detail categories are common for closed stiffener orthotropic decks, and cracks in these detail categories in real bridges have been reported [13].

In this study, the three lanes (see Fig. 1 (b)) downstream of Fengxi Bridge were chosen, and a test truck in tandem was applied to apply a series of controlled load tests. Fig. 3 shows the axle weights and geometry of the truck. To better control the transverse loading positions of the loading vehicle, the truck was driven from various transverse loading positions at the beginning line to the end line at a low speed $v = 5$ km/h, and the spacing between each transverse loading position was 100 mm. When the vehicle was driven along the first lane or the third lane, the measured strain results were generally relatively small. Therefore, we focus mainly on the response of the orthotropic steel deck when the vehicle was located between the #5 rib and #9 rib along the lanes. Because the measured result is expected to be small when the vehicle is far from the strain gauge, only the test region with a length of 60 m is considered, as shown in Fig. 1 (a).

4. Measured response

AS the vehicle slowly travelled from the beginning line to the end line, the strain measurements were continuously recorded. However, the strain measurements of the orthotropic steel deck cannot directly reveal its fatigue characteristics. Therefore, the elastic modulus of the steel was introduced to determine the corresponding stress of the deck. Next, a low-pass FFT filter was applied to eliminate the contributions of high-frequency noise.

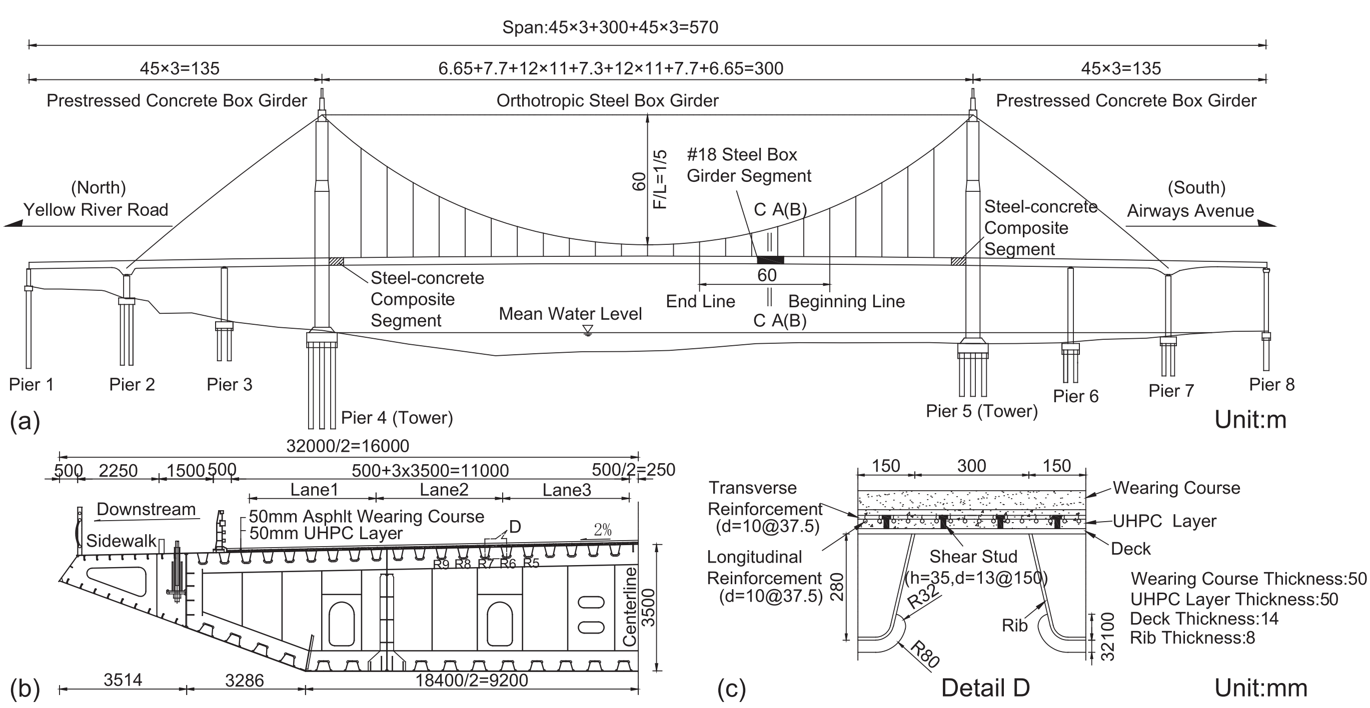

Fig. 1. Overview of the Fengxi Bridge: (a) elevation view; (b) half-cross-section of the steel box girder; (c) details of the lightweight composite deck.