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Experimental investigation on hybrid GFRP-concrete decks with T-shaped perforated ribs subjected to negative moment

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HIGHLIGHTS

- Proposed a hybrid GFRP-concrete deck system with T-shaped perforated ribs.
- Experimentally investigated the failure behavior of hybrid decks under negative moment.
- Simplified calculation methods were proposed to evaluate the strength, crack spacing.

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ABSTRACT

This paper proposes a hybrid glass fiber reinforced polymer (GFRP)-concrete deck consisting of pultruded GFRP plate with T-shaped perforated ribs in tension part and reinforced concrete in compression part. To better understand the structural behavior of the proposed hybrid deck over main girders in the transverse direction (perpendicular to the traffic direction), static tests on five full-scale deck models were conducted under negative bending moment. The main parameters of these experimental deck models were reinforcement ratio and the presence/absence of bent-up bars. The load-displacement relationship, ultimate capacity, strain distribution of GFRP plates and steel bars, and crack development were measured during the test. Experimental results indicated that flexural and shear failure modes occurred depending on the reinforcement ratio and the presence/absence of bent-up bars. The arrangement of the bent-up bars near the negative moment region can increase the ultimate loading capacity especially with respect to shear strength, but has little influence on the stiffness of the hybrid deck. GFRP T-shaped ribs are effective in controlling cracking. Simplified calculation methods were proposed to evaluate the flexural and shear strength and to predict the average crack spacing, which were calibrated by experimental results. The agreement of theoretical results with experimental ones demonstrates the accuracy and effectiveness of proposed equations for estimating the ultimate capacity and cracking behavior of such hybrid GFRP-concrete decks.

1. Introduction

Concrete and steel bridges are facing major challenges with respect to deterioration of corrosion prone components and fatigue damage to their decks. Nearly 25% of 607,380 bridges in a U.S. database were reported to either structurally deficient or functionally obsolete in 2013 [1], which necessitates large annual expenditures for rehabilitation and maintenance of such bridge structures. Thus, there has been a search for new materials and cost-effective solutions to build or replace the bridge systems, especially for bridge decks. Fiber reinforced polymer (FRP) composites are one of the viable alternative materials due to their high strength to weight ratio, corrosion resistance and excellent fatigue performance [2–4]. Such attributes have been demonstrated in rehabilitation and new projects over the last few decades.

Various all-FRP deck systems have been proposed, and they can be classified into two construction configurations [5,6]: 1) bonded pultruded profiles, consisting of different triangular single or dual-cell sections [7,8], box sections [9] or trapezoidal dual-cell sections [10]; and 2) sandwich forms with different core structures, such as corrugated core [11]. Compared with steel and concrete bridge decks, all-FRP decks are much lighter and more convenient to install. However, all-FRP deck systems exhibit some weaknesses, including high initial costs and low stiffness, which have hindered their widespread application. To this end, hybrid bridge decks

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based on a combination of FRP and concrete have been proposed [12,13]. Not only can the high strength of FRP be utilized effectively, but also the FRP profiles can serve as permanent formwork to significantly reduce construction time and labor cost.

Currently, several researchers have developed different types of hybrid FRP bridge decks. Reising *et al.* [14] applied four FRP deck systems, including two types of hybrid decks, within a bridge to assess installation issues, connection details and specific construction techniques. Their research also identified shortcomings in terms of handling, performance, and serviceability. Keller *et al.* [15] proposed a hybrid sandwich bridge deck, constituted by a GFRP sheet with T-upstands for the tensile component, a core made of lightweight concrete and a compressive component made of ultra-high performance reinforced concrete. He *et al.* [16] proposed a novel corrugated plate system, and conducted sand filling tests and static flexural load tests. The experimental results indicated that stiffness and strength of GFRP plate under construction loading satisfied the requirements of relevant codes. They also found that both surface treatments and penetrating bars can improve the connection between the GFRP plate and concrete. Fang *et al.* [17] experimentally studied the flexural behavior of a developed composite deck consisting of an FRP face sheet as the bottom face of the slab, a molded FRP grid on top of the FRP face sheet, and a top layer of concrete.

When hybrid decks cross the main girders in the horizontal direction, top concrete is vulnerable to tensile cracks due to negative bending moment in that region. Such cracking of concrete increases deflections, and causes the structural behavior to be strongly nonlinear even at low stress levels. Honickman *et al.* [18] conducted an experimental and analytical study on hybrid GFRP-concrete girders with a trapezoidal hat-shaped GFRP sheet to evaluate their structural behavior in both positive and negative bending moment regions. Xue *et al.* [19] performed an experimental study on the composite performance of FRP-concrete composite slabs under positive and negative loads. Some codes and guidelines [20,21] address the design of hybrid decks under positive moment by assuming the GFRP plank acts as reinforcing bars in concrete members, and present three different failure modes of hybrid decks under positive bending moment: flexural, diagonal shear and longitudinal shear-bond failure. Zuo *et al.* [22] conducted an experimental investigation on the structural behavior of a developed hybrid deck with GFRP T-shaped perforated ribs under positive bending with five test parameters, namely: (i) hole spacing, (ii) presence of bent-up bars, (iii) quality of the surface treatment of GFRP composites, (iv) deck depth, and (v) type of reinforcements. Experimental results identified three different typical failure modes: flexural, diagonal shear and longitudinal shear failure. However, there is little research that specifically relates to experimental or analytical investigation on the structural behavior in the negative moment region of hybrid GFRP-concrete decks. Moreover, in the negative moment region, cracking should be limited to ensure level that will not be expected to affect the proper function and durability of the structure. Influence of GFRP member on concrete crack propagation should also be carefully investigated in order to predict crack width and spacing accurately.

The primary objective is to evaluate a newly developed hybrid GFRP-concrete deck, combining of a pultruded GFRP bottom plate with T-shaped perforated ribs and concrete, and experimentally investigate its static behavior under negative moment. Five full-scale models differing in reinforcement ratio at the top layer, and in presence/absence of bent-up bars, were tested under negative moment to evaluate the load carrying capacity, failure modes and anti-cracking behavior. The experimental program examines the load and displacement relationship, ultimate strength, distribution of cracks, relative slip between GFRP plate and concrete, and strain distributions in GFRP plate and reinforcement bars. Simplified calculation methods are proposed to estimate the capacities of the deck system with respect to flexural and shear failure. A modified equation for average crack spacing is also provided. The experimental results serve to calibrate the equations and demonstrate their applicability.

2. Proposed deck systems

2.1. Descriptions of deck systems

The proposed hybrid GFRP-concrete bridge deck is shown in Fig. 1, and its structural performance under positive bending moment has been studied experimentally in [22]. The deck consists of a pultruded GFRP bottom plate with T-shaped perforated ribs for the tensile zone and reinforced concrete for the compression part. The GFRP plate and ribs also act as permanent formwork for concrete pouring. To achieve perfect bond at the interface between the GFRP plate and concrete, the surface of GFRP plate was coated with an epoxy-sand mixture. In addition, there are two other connection mechanisms: one is shear and uplift effects of GFRP T-shaped ribs, which is similar to the effect of densely placed headed studs; the other mechanism is formed by the penetrating bars through the holes in GFRP T-shaped perforated ribs, which act as perfobond rib connectors (PBLs) [23].

The structural form and dimensions of the pultruded GFRP plate with integral T-shaped ribs are presented in Fig. 2. The PBLs on the T-shaped ribs provide the mechanical connection to the concrete. To fulfill different width requirements, standard GFRP plates were interconnected by lap splicing of the ribs and epoxy resin bonding. Stainless steel bolts were also used to enhance the connection simultaneously.

A schematic view of a portion of the proposed composite bridge structure is shown in Fig. 3. The hybrid GFRP-concrete deck is supported by steel girders, spaced at 1800 mm center-to-center. Including two overhang portions, the overall length of the deck is 3500 mm; the depth of the deck is 240 mm. These dimensions of the composite bridge deck were determined in accordance with Eurocode 4 [24]. For wheel loads within the deck span (i.e., running between the girders in the traffic direction), the hybrid deck experiences negative moments over the girder. To better understand such structural behavior, static tests on full-scale deck models were conducted. To facilitate the experimental program, symmetric portions of the full-scale bridge decks were constructed and loaded.

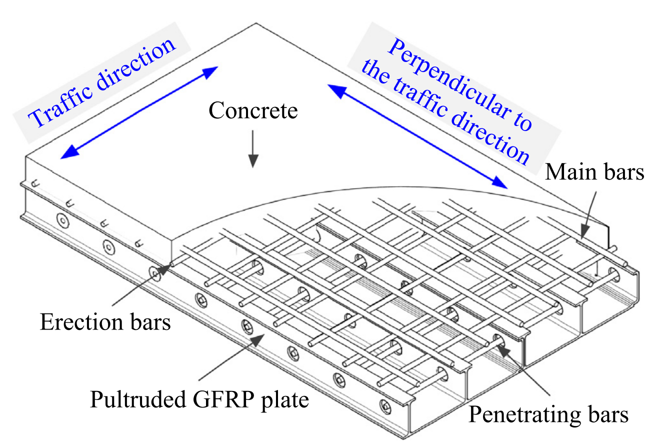

Fig. 1. Hybrid GFRP-concrete bridge deck structure.