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Flexural performance of a hybrid GFRP-concrete bridge deck with composite T-shaped perforated rib connectors

Yize Zuo[a], Ayman Mosallam[b], Haohui Xin[a], Yuqing Liu[a,*], Jun He[c]

[a] Department of Bridge Engineering, Tongji University, Shanghai, China
[b] Department of Civil and Environment Engineering, University of California, Irvine, CA, USA
[c] School of Civil Engineering, Changsha University of Science and Technology, Hunan, China

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ABSTRACT

In this study, the flexural performance of an innovative hybrid GFRP-concrete deck is evaluated. The proposed hybrid composite deck consists of a pultruded GFRP plate with T-shaped perforated ribs for resisting tensile stresses, while concrete with reinforcements is placed at the compressive side of the deck. In order to better understand the flexural performance of proposed hybrid decks under sagging moment, a total of six full-scale hybrid deck models were experimentally investigated. Five test parameters were considered, namely: (i) hole spacing, (ii) presence of bent-up rebars, (iii) quality of GFRP composites surface treatment, (iv) deck depth, and (v) type of reinforcements. Experimental results identified three different typical failure modes, namely: diagonal and longitudinal shear, as well as flexure. Furthermore, it was found that the inclusion of bent-up rebars, sand bonded to GFRP plates surfaces, and increasing deck thickness enhance the ultimate strength of the proposed hybrid deck. It was also concluded that the hole spacing and the reinforcement type have negligible influence on ultimate capacity of the proposed deck. Moreover, finite element models considering the laminate damage based on Hashin's theory were built and load transfer and failure mechanisms of GFRP perforated ribs were discussed. The validity of the proposed analytical method, with respect to failure mode and ultimate strength for the hybrid deck, was confirmed through the close correlation between analytical and experimental results.

1. Introduction

Pultruded glass fiber reinforced polymer (GFRP) materials are being increasing used in various civil infrastructures, as well as in other industrial applications [1,2]. In the last two decades, applications of GFRP composites in highway structures focused on bridge decks rehabilitation and replacement due to their attractive features to bridge engineers such as, high-strength-to weight ratio, ease of site assembly, high corrosion resistance as compared to other conventional materials such as steel, concrete and timber as well as the resistance to fatigue [3–8].

In order to make a better use of different materials, hybrid structures combining GFRP composites with conventional materials, such as concrete, have been developed in order take advantage of the superiority of each material that results in cost reduction and enhancement of the hybrid bridge decks [9–12]. In these deck systems, not only can GFRP structural members act as tensile reinforcement for the hardened concrete, but also they serve as stay-in-place (SIP) formwork to reduce construction time and labor cost significantly.

To achieve the desired composite action, longitudinal shear forces need to be transferred between the GFRP profile and the concrete. Several different types of interfacial shear connections have been proposed. Coated sand layer is one of the most common means for such connection. Although the coating layer provides high-performance shear connection using friction that results in a negligible cripple to the fiber reinforced polymeric (FRP) composites and concrete components, the strength of adhesives bondline in the normal direction is usually less than 1.0 MPa, which is much weaker than what is needed for normal splitting [13]. Moreover, brittle failure modes and the ageing problem in this case may become the governing factor [14–16]. Another technique is using FRP shear keys to promote the desired composite action, however, their connection with the FRP girder is notably complicated, which makes deck construction difficult and material-consuming [17]. In recent years, perforated FRP rib shear connectors have been proposed, that use the same concept as the perfobond rib connectors (PBLs) in steel-concrete composite beams [18–21]. These shear connectors can effectively prevent the normal debonding between FRP and concrete. In addition, the concrete wedge and penetrating bars present longitudinal shear resistance [22,23].

* Corresponding author.
E-mail address: yql@tongji.edu.cn (Y. Liu).

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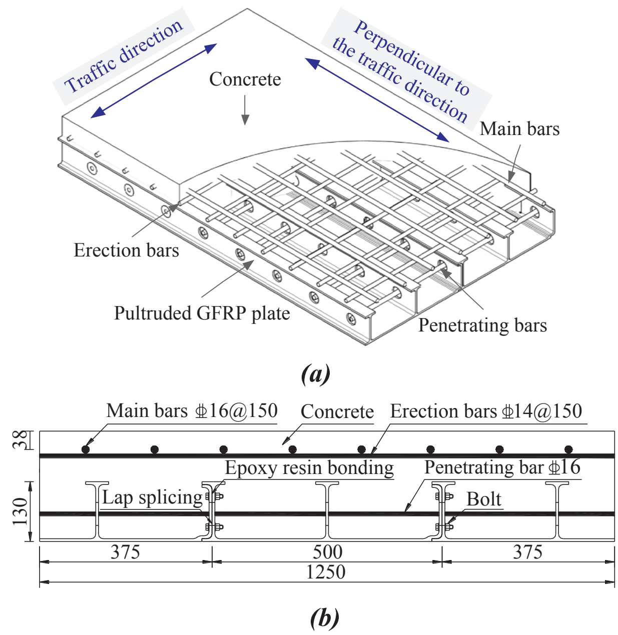

Fig. 1. Proposed hybrid GFRP-concrete bridge deck (mm): *(a) schematic view; (b) cross-sectional dimensions.*

A considerable number of studies related to different types of hybrid deck systems have been conducted, including developing GFRP profiles geometric configurations and experimental works. Davalos et al. [24] presented an analytical procedure for FRP honeycomb sandwich panels based on analytical and experimental studies. Aref et al. [25,6] performed experimental tests and numerical analysis on a hybrid FRP concrete bridge superstructure system comprised of a layer of concrete and three trapezoidal GFRP tubes surrounded by an FRP outer shell. Their experimental tests showed that the presence of concrete increased the deck stiffness by 35%. Keller et al. [26] proposed a hybrid sandwich bridge deck, constituted by a GFRP sheet with T-upstands for the tensile skin, a core made of lightweight concrete and a compressive skin made of ultrahigh performance reinforced concrete. He et al. [27] studied the influence of different connection details on the ultimate strength of hybrid decks by static bending tests, which the hybrid deck consisted of the corrugated pultruded GFRP plate and the reinforced concrete. Five bridge decks casted onto GFRP permanent forms with T-shape ribs were evaluated by Nelson et al. [28]. Due to its geometry, this system promoted good mechanical interlock between the FRP form and concrete, reducing the need for bonding agents. The reviewed research work shows a high potential for hybrid FRP and concrete construction where each material optimally used. However, premature web buckling of hollow FRP sections, a brittle behavior, insufficient interface capacity to provide full composite action between the FRP and concrete were still the particularly concerned problems. Hybrid GFRP-concrete deck with T-shaped perforated rib shear connectors could provide a potential way to address some of these problems.

The primary objective of this study is to experimentally investigate the flexural behavior of proposed hybrid GFRP-concrete decks under sagging moment. A total of six full-scale models were tested under sagging moment to evaluate the ultimate strength and failure modes. The test parameters include the hole spacing, the presence of bent-up rebars, the GFRP surface treatment, the height of deck and the type of bars. Furthermore, finite element models considering the laminate damage based on Hashin's theory were built and load transfer and failure mechanisms on of GFRP perforated ribs were discussed. Based on the test results, theoretical equations for ultimate strength estimation are assessed for limit states associated with flexure and shear failure mode. Accuracy of the equations is demonstrated through comparison with the experimental results.

2. Descriptions of proposed hybrid deck systems

Fig. 1(a) shows a schematic view of the proposed hybrid GFRP-concrete bridge deck in this study. It consists of the pultruded GFRP bottom plate with integral T-shaped perforated ribs, reinforcements and concrete. The GFRP plate and T-shaped ribs serve as tensile reinforcements with the same function of common bottom longitudinal reinforcing bars, also serve as permanent formwork for the concrete casting. The longitudinal stiffeners of the GFRP plates, the T-shaped ribs, provide the shear and uplift effect. Meanwhile, the penetrating bars through the holes in GFRP T-shaped perforated rib connectors act as PBLs, as well as transfer the transverse load of the deck systems. In addition, sand was also bonded to the GFRP plates with epoxy to achieve satisfactory bond between the smooth surface of GFRP plate and the concrete.

Fig. 1(b) shows the cross-sectional dimensions of the proposed hybrid deck. Reinforcing steel or GFRP bars with a diameter of 16.0 mm were used for longitudinal reinforcements, with a 30.0 mm concrete cover. As was studied in [29], steel rebars were used to provide ductility to the deck over the supporting girder, where it was subjected to negative moment in the transverse direction. That is why the reinforcements on the top can use steel rebars even if steel materials are vulnerable to corrosion. In order to fulfill different width requirements, standard GFRP plates were interconnected by lap splicing of the ribs and epoxy resin bonding. Simultaneously, stainless steel bolts were also used to enhance the connection.

The dimensions and image of the GFRP T-shaped perforated ribs connectors which were pultruded integrally, are presented in Fig. 2. The thickness of the GFRP plate was 6.0 mm for high tensile strength of GFRP. The height of GFRP T-shaped ribs is 130 mm, and their distance is 250.0 mm in the transversal direction. There is still no design information available for GFRP perforated ribs connectors. Based on the study results of PBLs in steel-concrete composite beams [18–21], the hole diameter (D) is generally assumed to be about half the height of the perforated rib, and the hole spacing that produces the maximum shear resistance varies from 2.0D to 2.5D. However, the shear strength of GFRP ribs is much lower than that of steel ribs, thus the hole spacing of GFRP plates is determined as 4.0D to avoid the premature shear failure of GFRP ribs. The diameter and center-to-center spacing of holes for the GFRP perforated rib connectors in this study were chosen as 50.0 mm and 200.0 mm, respectively.

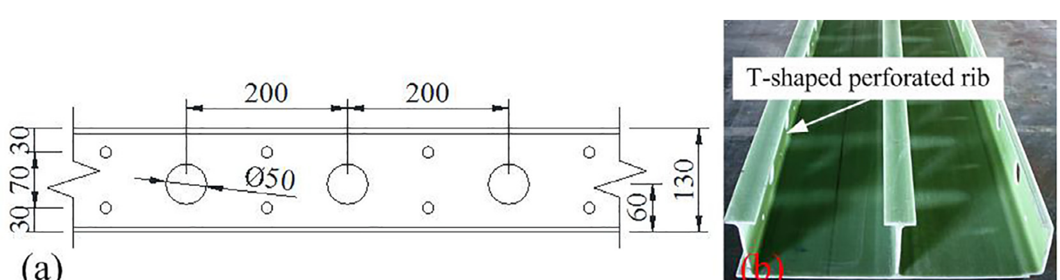

Fig. 2. Dimension and image of the GFRP T-shaped perforated ribs connectors (mm).