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Performance of a lightweight GFRP composite bridge deck in positive and negative bending regions

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ABSTRACT

This paper presents results from an experimental and analytical study of a newly developed lightweight composite bridge deck system composed of pultruded trapezoidal GFRP tubes and outer wrap. Panels with different grout materials and grouting patterns were evaluated and compared in terms of flexural stiffness. Two-span tests were performed on non-grouted and epoxy grouted panels to simulate a multi-girder bridge configuration and to evaluate their structural behavior in both positive and negative bending regions. Test results showed that the epoxy grouted panel meets the AASHTO deflection requirement (L/800) and performed well under service loads. An analytical model was developed to predict the load–deflection response of grouted and non-grouted panels at incremental load steps, even beyond the uncracked stage. The proposed model shows that shear deformation must be considered in order to accurately predict the behavior of GFRP panels in multi-girder bridges.

1. Introduction

According to the 2013 American Society of Civil Engineers (ASCE) report for America's infrastructure, almost 25% of the US's 607,380 bridges are either structurally deficient or functionally obsolete [1]. Lack of adequate funds for maintenance of bridge structures over many decades has accelerated the deterioration of corrosion prone components made of steel or reinforced concrete. Thus, state and federal agencies are interested in exploring the use of new materials and structural systems with minimum maintenance costs (or inherently high corrosion resistance) to build or replace bridge systems, particularly bridge decks. FRP composites constitute a viable alternative due to their high strength/weight ratio, corrosion immunity, and high fatigue strength. In the last few decades, structural applications of FRP composites in civil infrastructure systems have been developed. Among the uses of FRP composites in highway structures, bridge decks for rehabilitation and new construction have drawn significant attention because of their inherent advantages in strength and stiffness per unit weight as compared to traditional steel reinforced concrete decks [2].

Various all-FRP deck systems have been developed and implemented in USA and Canada, such as Hardcore system, EZSpan system, Superdeck system and DuraSpan system. These all-FRP deck systems can be classified into two major categories according to their construction - sandwich versus adhesively bonded pultruded shapes [2]. Sandwich decks provide design flexibility of the deck depth and architecture of the face sheet, while decks assembled by adhesively bonded pultruded shapes can take advantage of an optimization of the cross section design as well as higher manufacturing quality control. In addition, the typical weight of an all-FRP bridge deck is only about 20% percent that of a conventional concrete bridge deck [3], which facilitates the transportation and installation of deck panels.

Despite the advantages of all-FRP bridge deck systems, their initial costs (materials and construction) is still higher than those of deck systems made of conventional materials. Bakis et al. [2] indicated that the cost of an FRP deck (per area) could be up to more than twice the cost of a deck made of conventional materials. Cheng and Karbhari [4], after reviewing the data of FRP bridges from 1980 to 2006, concluded that the design of an all-FRP bridge deck is driven by stiffness thus limiting the optimization of the material used in a cross section. Thus, hybrid bridge systems combining FRP composites with components made of traditional materials, such as concrete, have been developed in order to reduce the cost and enhance the performance of FRP bridge components. In the 1990s Bakeri and Sunder [5] introduced the hybrid concept for FRP slabs stating that in their cross section the compressive stresses are carried by the concrete and the tensile stresses are taken by the FRP component. Several researchers have further developed the hybrid concept into specific bridge applications,

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such as decks and hybrid girders [6,7]. Aref et al. [8,9] 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 panel stiffness by 35%. Johnson et al. [10] compared the performance of a GFRP bridge deck system with and without concrete topping, and found that a panel without concrete topping has only 50% of the stiffness and weight of the hybrid panels. They also found that the bond between the concrete and the GFRP panel could be inadequate even with the use of shear keys. Among all these applications of the hybrid concept into bridge decks and girders, concrete is the most common material used for the top layer of the structure. However, in cases when the deck is placed on a multi-girder bridge, thus subjected to negative bending over the interior girders, the concrete layer is highly vulnerable to tensile cracking. Thus, an alternative material or hybrid configuration should be investigated.

The primary objective of this study is to investigate the flexural behavior of a newly developed hybrid deck system combining the GFRP pultruded tubes with different grout material and grouting pattern, and to verify the feasibility of such deck panel on multi-girder bridges. Two types of grout and two grouting patterns were evaluated in terms of flexural stiffness. Experimental tests of grouted and non-grouted deck panels were performed in single span and two-span conditions to assess the flexural behaviors of the panels in positive bending and negative bending regions. An analytic model was developed to predict the load–deflection response of these deck panels with and without grout. The behavior of the hybrid deck panel in different loading conditions is discussed in the following sections and comparisons of the analytical model and experimental data are presented.

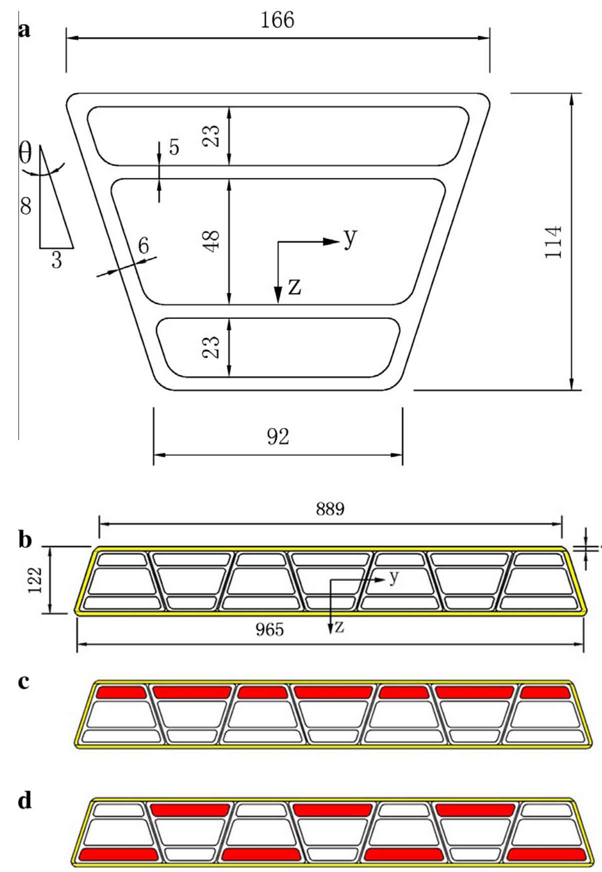

Fig. 1. Cross section of tube and panels (dimensions in mm). (a) Pultruded tube; (b) non-grouted panel; (c) grouted panel with narrow side cells filled pattern; and (d) grouted panel with alternate cells filled pattern.

2. Description of the test specimens

An innovative FRP bridge deck system was developed as part of a "Highways for LIFE Technology Partnerships Program", sponsored by the Federal Highway Administration. The deck was intended for movable or weight-restricted bridges whose dek system had supporting stringers spaced up to 1.5 m. The deck design was based on a pultruded system developed by a research team at the University at Buffalo [9]. As part of the FHWA project, improvements were made to the cross section design, materials used, and fabrication process, in order to enhance the deck performance and reduce its cost [11].

The basic component of the deck panel – tubes, were produced by an FRP manufacturer using the pultrusion process. An epoxy Vinyl Ester resin with a high degree of fire retardance was used as matrix. The tube reinforcement is comprised of E-glass rovings, woven mat, and chapped strand mat. Details of the fiber layout of the pultruded tube flanges and webs as well as the fire performance of the deck panel can be found in [11]. Fig. 1a shows the dimensions of the tube cross section; the thickness of all flanges is 5 mm, and the thickness of webs are 6 mm.

To fabricate the FRP deck panel, seven pultruded tubes were glued together using epoxy and then wrapped with additional glass fiber fabrics. The vacuum-assisted resin transfer molding (VARTM) method was used by a second composite manufacturer to create an integral deck panel with outer wrap. The glass fiber fabrics in the outer wrap consisted of layers of stitch-bonded biaxial fabrics, and continuous filament mats (randomly oriented fiber). These fabrics are designed specifically for resin infusion processes with the continuous filament mat providing a medium to improve resin flow into the reinforcement fiber during fabrication. Details of the outer wrap configuration can be found in [11]. The panel cross section dimensions are shown in Fig. 1b.

The top and bottom bottom cells of the pultruded tubes were designed to be filled with grout, if needed. Two types of grout were used in this study, non-shrink cement based grout and epoxy based grout; they will be referred to as cementitious grout and epoxy grout, respectively, in the following discussion. Two different grouting patterns were explored for the grouted panels, shown in Fig. 1c and d. The non-grouted panel weights approximately 78 kg/m^2 (not including the wearing surface) while the grouted panel weighs about 122 kg/m^2 without a wearing surface, both options are much lighter than conventional bridge decks made of concrete (on the order of 480 kg/m^2). A total of eight grouted panels and four non-grouted panels were delivered to the Civil Infrastructure Testing and Evaluation Laboratory (CITEL) at Penn State University; all the panels have the same length of 3.35 m.

3. Experimental program

The objective of the experimental program was to evaluate the flexural behavior of grouted and non-grouted panels in single span and two-span conditions. Single span flexure tests of grouted and non-grouted panels were performed to evaluate the behaviors of the panels in positive bending regions, and to compare the effect of different grouting patterns (including non grouting options) in the flexural stiffness of the panels. Two-span flexure tests on a non-grouted panel and an epoxy grouted panel were conducted to assess the behavior of the epoxy grouted panel in negative