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Evaluation of sandwich panels with various polyurethane foam-cores and ribs

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ABSTRACT

The objective of this study was to evaluate three potential core alternatives for glass fiber reinforced polymer (GFRP) foam-core sandwich panels. The proposed system could reduce the initial production costs and the manufacturing difficulties while improving the system performance. Three different polyurethane foam configurations were considered for the inner core, and the most suitable system was recommended for further prototyping. These configurations consisted of high-density polyurethane foam (Type 1), a bidirectional gridwork of thin, interconnecting, GFRP webs that is in-filled with low-density polyurethane foam (Type 2), and trapezoidal-shaped, low-density polyurethane foam utilizing GFRP web layers (Type 3). The facings of the three cores consisted of three plies of bidirectional E-glass woven fabric within a compatible polyurethane resin. Several types of small-scale experimental investigations were conducted. The results from this study indicated that the Types 1 and 2 cores were very weak and flexible making their implementation in bridge deck panels less practical. The Type 3 core possessed a higher strength and stiffness than the other two types. Therefore, this type is recommended for the proposed sandwich system to serve as a candidate for further development. Additionally, a finite element model (FEM) was developed using software package ABAQUS for the Type 3 system to further investigate its structural behavior. This model was successfully compared to experimental data indicating its suitability for parametric analysis of panels and their design.

1. Introduction

The majority of highway bridge decks are constructed with steel-reinforced concrete. The life-span of such materials can be significantly reduced by environmental conditions combined with wear from traffic, de-icing chemicals, and insufficient maintenance. As a result, transportation agencies have been endeavored to find new cost-effective, reliable construction materials. Fiber reinforced polymer (FRP) has shown great promise in eliminating corrosion concerns while also achieving a longer life-span with minimal maintenance [1]. FRP has been used for columns [2–4], beams [5,6], and panels [7–10]. FRP sandwich panels have many advantages, such as high flexural stiffness, strength, and environmental resistance, as well as reduced weight and life cycle cost. Using FRP deck panels should also contribute to accelerated bridge construction. These advantages make FRP sandwich panels an excellent candidate for construction of bridge decks.

Sandwich panels are often composed of two thin facings that are bonded to a much thicker core. The facings are typically made of high strength and stiffness material. The core usually consists of a rigid-foam, which has a low to moderate strength and stiffness [11]. However, the core design is industry-related. The facings are largely responsible for carrying flexural loads while the core provides shear capacity and integrity of the structure [12]. Many alternative forms of sandwich panels can be accomplished by combing different facings and core materials combined with varying geometries. As a result, optimum designs can be produced for specific applications [11].

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Researchers and manufacturers have developed many FRP bridge deck designs with honeycomb and cellular cores made of E-glass reinforced polyester or vinyl ester resin. These designs have primarily been manufactured using filament winding, hand lay-up, and pultrusion methods [13]. A honeycomb core is one of the famous cores that being used in sandwich panels, implemented in bridge decks [8,14–20]. The honeycomb core consists of sinusoidal wave corrugations and straight components sandwiched between the facings. Testing showed that this type of panels is effective in providing high mechanical performance for minimum unit weight [14,19].

Researchers have proposed alternative forms for sandwich panels. Potluri et al. [21] proposed a conventional sandwich panel where the top and bottom facings were separated by a foam core. In their study, they introduced FRP stitches to improve the foam core performance. The stitches were used also to prevent core-to-facing debonding. It was found that both static and fatigue structural behavior can be improved by stitching together the top and bottom facings. Hassan et al. and Reis and Rizkalla [22,23] proposed an alternative system for FRP bridge decks. The proposed panel used three-dimensional fibers (stitches through foam cores) to connect the top and bottom GFRP facings. They observed that the delamination concerns were overcome. In addition, the fiber reinforced stitches increased significantly the core shear modulus. Dawood et al. [24] studied the fatigue behavior of sandwich panels with flexible and stiff cores. They found that the panels with flexible cores exhibit less degradation than those with stiffer cores due to the higher induced shear stresses at the same level of applied shear strain. Zureick [25] used finite element analysis to study different cross-sections of simply supported FRP decks. This study compared four different cross-sections, concluding that the box shaped and V shaped cores behaved much better than the other sections. Although the results from these studies provided a noteworthy understanding of FRP sandwich panel's behavior, most of these results cannot be extrapolated to other products.

The connection between the deck panels to the underlying steel girders is typically made using adhesive glue at the interface, shear studs, bolted connection, or steel clamps in a simply supported condition [26–29].

2. Paper scope and objectives

In the present study, small-scale FRP sandwich beams having three different foam core configurations (see Fig. 1) were investigated. The proposed system could reduce the initial production costs and the manufacturing difficulties while improving the system performance. The facings of the proposed three sandwich beams consist of E-glass woven fabric within a compatible polyurethane resin. Each configuration uses polyurethane foam as an infill material for the inner core. The investigated core configurations include high-density polyurethane foam (Type 1), a gridwork of thin, interconnecting, GFRP webs that is infilled with low-density polyurethane foam (Type 2), and GFRP trapezoidal-shaped infilled with low density polyurethane foam (Type 3). The polyurethane foam was chosen because it provides several advantages. These advantages include:

- Lower material and labor costs.
- Higher impact resistance and damping.
- Compatible material to the polyurethane resin, which aids in the infusion process and bonding with the face sheets.

A polyurethane resin system was used in the proposed sandwich beams as it has good high resistance and superior mechanical properties compared to polyester and vinyl ester [30]. This resin system was also chosen because it can reduce the initial costs of the sandwich beams. The one-step Vacuum Assisted Resin Transfer Molding (VARTM) process was also chosen to manufacture beams as it has a lower production cost than other manufacturing methods. For instance, the production cost of pultruded deck panels is approximately five times the production cost of hand lay-up deck panels [31]. The VARTM process can be used to manufacture both small and large FRP bridge deck panels. Although, polyurethane resin has a low pot life, recent modifications to the resin enabled it to be used with the VARTM process. A thermoset polyurethane resin with a longer pot life developed by Bayer MaterialScience was used in this study to manufacture the sandwich beams. All specimens were manufactured in the Composites Manufacturing Laboratory, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology.

One of the greatest challenges faced by structural sandwich beams/panels is that the inner core has low transverse stiffness and strength. As a result, these panels are vulnerable to in-plane shear, wrinkling instability, and face-to-core deboning [32]. Therefore, the three design criteria considered in this study were chosen to improve the core's mechanical performance. The high-density foam in the first type was used with no webs in the core in an attempt to minimize both weight and cost. The cores in the second and third types consisted of low-density foam to minimize the weight reinforced with GFRP webs. Furthermore, the web elements of Types 2 and 3 potentially will delay both delamination failure and local crushing.

This paper compares the structural characteristics of the three proposed sandwich beam systems. The compressive and tensile strengths were assessed through the flatwise compressive and tensile tests of small sandwich cubes and coupon tests. The flexural strength and bending stiffness of each core system were also evaluated through three and four-point bending tests. The possible modes of failure of the different core configurations were also determined. A finite element model (FEM) was also developed for the Type 3 system and verified using the experimental results. The FEM was used for a better understanding of the structural behavior of this sandwich beam type.

A full-scale of Type 3 system was recently manufactured by the Structural Composites, Inc [33]. Based on the manufacturer, the resulting costs of the panel system was less than one half the cost of a comparable honeycomb FRP deck construction. Additionally, on a production run for an actual bridge, the manufacture estimates a further decrease in unit costs of 40%–50%, bringing the FRP deck alternative in line with initial costs of reinforced concrete decks.

3. Experimental program

This study examined the cross-sections of three different configurations of the closed-cell polyurethane infill-foam beams (see Fig. 1). The facings of the three types consisted of three plies of bidirectional E-Glass woven fabric (WR18/3010) infused with a compatible polyurethane resin. The core of Type 1 was comprised of high-density polyurethane foam that had a mass density of 96 kg/m^3. The Type 2 core consists of thin, interconnecting, glass fiber/resin webs that form a bidirectional FRP gridwork that is infilled with a low-density polyurethane foam of 32 kg/m^3. The Type 3 core was comprised of a trapezoidal-shaped, low-density, polyurethane foam and three-ply web layers (E-BXM1715).

The dry fabric and foam were stacked together in a rigid aluminum mold. High permeability layers placed over the fibers reduced infusion time, and a standard peel ply prevented the resin from adhering to the vacuum bag. Then, the thermoset polyurethane resin was infused through the vacuum-assisted process.