DEVELOPMENT OF MODULAR GFRP BRIDGE DECKS

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ABSTRACT

The demand for the development of more efficient and durable bridge decks is at the forefront of the priority of highway authorities worldwide. Conventional steel reinforced concrete and steel decks are prone to corrosion which drastically reduces their service life. Replacement or repair of concrete bridges has also proven to be very costly, time-consuming and disruptive to traffic flow. This paper proposes a new innovative glass fibre reinforced polymer (GFRP) bridge deck as an alternative and solution to these problems.

The proposed GFRP bridge deck consists of a series of equilateral triangular tubes produced by the filament winding process and combined in specific configurations appropriate for highway bridge decks. Wardrop Engineering Inc./Faroex Ltd. have identified fundamental economic and functional improvements over existing composite technologies that are under development, and have a patent pending on their design. In the design, glass fibres and resin are wound at varying angles to achieve the most desired transverse and longitudinal strengths. Pultruded glass fibre bars and plates are combined with the modular tubes to create a single deck module. These modules are designed to be shipped to the site of the bridge and installed within a few hours.

This paper provides a description of the deck, fabrication process and preliminary results of the experimental program conducted at the University of Manitoba. The deck modules are tested in simply supported conditions under a simulated wheel load and loaded to failure to examine the behaviour at service loading conditions as well as capacity and failure mode.
INTRODUCTION

Highway authorities worldwide are facing the need for repair and/or replacement of thousands of highway bridge decks. The cost of this extensive rehabilitation is estimated in the billions of dollars, therefore the task must be met with ingenuity and innovation.

It has been documented that over one-half of the United States’ 600,000 state, county and city bridges were built prior to 1940 (Zureick et al, 1995). These bridge decks are now reaching the end of their useful service lives. Conventional bridge decks reinforced with steel are susceptible to corrosion which is known to cause significant deterioration of the concrete. In addition, the inherent large weight of steel and concrete bridge decks reduces the structure’s load carrying capacity and consequently decreases its capability to meet today’s standard truckload demands. This combination of aging infrastructure, material degradation and substandard load ratings has led to as many as 200,000 US bridge structures being classified as functionally obsolete (Zureick et al, 1995).

Clearly, this problem cannot be remedied with the same materials that contributed to the problem in the first place. This paper proposes the use of a fibre reinforced polymer (FRP) material for an innovative bridge deck system.

BACKGROUND

FRPs offer a number of advantages over conventional materials, many of which have become familiar to industry. It has been reported that a GFRP bridge deck produced by Creative Pultrusions and Owens and Corning (1999) had 6-7 times the capacity of a reinforced concrete deck. Another inherent quality of an FRP deck is light weight. This allows for ease of handling, reduced labour and rapid installation onsite. Also the corrosion resistance of FRPs eliminates costly maintenance and repairs of bridge decks during their service life. Since FRP can be produced by a variety of methods, nearly any shape or size of component can be manufactured, providing design flexibility to the engineer.

Although research into composite bridges began a short 20 years ago, a considerable quantity of research has been performed. Much of the research is focussed on determining the most effective combination of deck configuration and manufacturing method to produce a cost-effective deck.

Leaders in this area include DuPont Composites (Bernetich et al, 1996), Creative Pultrusions (Owens Corning, 1999) and Martin Marietta Materials Inc., all of which have produced GFRP decks of varying configurations and manufacturing methods. These range from trapezoidal and triangular decks formed by pultrusion, to hybrid triangle-diamond shaped decks produced by the hand lay-up method.

This technology has advanced further with the recent installation of prototype GFRP decks in the United States. Creative Pultrusions installed two 9m long by 6.6m wide GFRP decks in West Virginia in 1997. Martin Marietta Materials Inc. installed two GFRP bridges
in the same year. Within the next 12 years, the National Composites Centre in Ohio, US plans to build over 100 composite bridges (Niehaus, 1999).

EXPERIMENTAL PROGRAM

The objective of this testing program is to evaluate the behaviour of GFRP bridge deck modules under the effect of an HS-30 design truck load as specified by AASHTO. The deck modules were designed by Wardrop Engineering Ltd. and fabricated by Faroex Ltd. The experimental program was conducted at the W.R. McQuade Structural Lab at the University of Manitoba by the ISIS Canada research team.

The deck consisted of three triangular filament wound tubes, approximately 200mm in height. Due to the rounded corners of the triangular sections, there was potential for large voids at the top and bottom of the deck. To eliminate weaknesses associated with this problem (Karbhari, 1996), pultruded GFRP bars were placed in the section. GFRP plates were adhered to the top and bottom of the tubes to create one modular unit. These 15-mm thick plates consisted of five laminates bonded together; three with fibres in the longitudinal direction and two with fibres in the transverse direction. In addition, one of the three decks was fabricated with a GFRP mat wrapped between the tubes to investigate its effect on deck performance. A schematic of the deck cross section is shown in Fig. 1.

![Fig. 1: Schematic of Deck Cross Section](image)

The fabrication process may be summarized as follows:

1. Triangular shaped styrofoam mandrels were custom-made, as shown in Fig. 2. A thin layer of epoxy-prepregnated chopped fibres was applied to strengthen the mandrel surface.

2. Three 3.5-m long mandrels were filament wound with Owens Corning glass fibre rovings as shown in Fig. 3. An eight layer laminate design was used, with a layering sequence of [90/±45/±10/±45/90]. A custom-made epoxy resin with a 24-hour pot life was used.

![Fig. 2: Mandrels](image)
3. The three triangular elements were placed on the GFRP plate and bonded with added resin. A GFRP mat was wrapped around the tubes in one of the three decks described in this paper, as shown in Fig. 4. The GFRP bars were placed between the tubes, as shown in Fig. 5.

4. The top plate was positioned and bonded with added resin. Upon completion of assembly, the deck was wrapped and sealed in a plastic bag, as shown in Fig. 6.

5. The deck was cured at 180°F for 8-10 hours, while a vacuum pump worked to remove excess resin from the deck and minimize voids. When curing was complete, the deck module was cut to the desired length.

The three prototype specimens were tested using seven flexural configurations. Parameters included: orientation of the deck during testing, condition of the deck plates and presence of fibre mat wrapping around the deck. Table 1 summarizes the specimen configurations used in this paper.
### Table 1: Specimen Designation

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>Orientation During Testing</th>
<th>Plate Condition</th>
<th>Filler Bar Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Basic Module</td>
<td></td>
<td>Bot.: Intact</td>
<td>Bot.: Intact</td>
</tr>
<tr>
<td>F1a</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Deck F1 Retested</td>
<td></td>
<td>Bot.: Partially Delaminated</td>
<td>Bot.: Intact</td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Basic Module</td>
<td></td>
<td>Bot.: Intact</td>
<td>Bot.: Intact</td>
</tr>
<tr>
<td>F2a</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Deck F-2 Retested</td>
<td></td>
<td>Bot.: Removed</td>
<td>Bot.: Removed</td>
</tr>
<tr>
<td>FR</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Mat wrapped deck</td>
<td></td>
<td>Bot.: Intact</td>
<td>Bot.: Intact</td>
</tr>
<tr>
<td>Deck FRa</td>
<td></td>
<td>Top: Intact</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Deck FR Retested</td>
<td></td>
<td>Bot.: Removed</td>
<td>Bot.: Intact</td>
</tr>
<tr>
<td>Deck FRb</td>
<td></td>
<td>Top: Removed</td>
<td>Top: Intact</td>
</tr>
<tr>
<td>Deck FR Retested</td>
<td></td>
<td>Bot.: Removed</td>
<td>Bot.: Intact</td>
</tr>
</tbody>
</table>

**Testing**

The deck was tested under simply supported conditions with a single 250x250mm point load applied at the centre of its 3m span. This load simulated the wheel load of a truck. The load was applied by a closed-loop 1000kN machine using stroke control at 0.75mm/min. Neoprene pads were located at the supports and the central loading point. The test setup is shown in Fig. 7.

![Fig. 7: Test Setup](image)

Deflections were measured using linear variable differential transducers (LVDTs) located at midspan and the supports. Strain gauges were also applied along the top and bottom plates to measure the strains at different load levels and locations.

**TEST RESULTS**

**Load-Deflection Behaviour**

All decks demonstrated similar linear behaviour under the applied load. This included a uniform stiffness throughout loading, interrupted by slippage of the bars and buckling of the plates as shown in Fig. 8 for Deck F2.
Upon unloading Deck F2 at a load level of 50kN and reloading, it was observed that the deck resumed its original stiffness without permanent deformation. At a load of 200kN it was observed that the GFRP bars slipped, causing a sudden load drop in load carrying capacity. The bar slip at failure is shown in Fig. 9. The uppermost ply of the top plate suffered local buckling at a load level of 300kN and the deck failed due to delamination of the bottom plate at a load level of 414kN.

![Fig. 8: Load-Deflection Behaviour in Deck F2](image1)

![Fig. 9: Bar Slip at Failure](image2)

**Failure Mode**

The three modes of failure observed were plate buckling, plate delamination and buckling of the tubes. Table 2 summarizes the important failure parameters for each test.

<table>
<thead>
<tr>
<th>Deck</th>
<th>Failure Load (kN)</th>
<th>Failure Mode</th>
<th>Maximum Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>190</td>
<td>Top plate buckled</td>
<td>33</td>
</tr>
<tr>
<td>F1a</td>
<td>365</td>
<td>Bottom plate delaminated</td>
<td>63</td>
</tr>
<tr>
<td>F2</td>
<td>414</td>
<td>Bottom plate delaminated</td>
<td>69</td>
</tr>
<tr>
<td>F2a</td>
<td>285</td>
<td>Top plate buckled and tube buckled</td>
<td>89</td>
</tr>
<tr>
<td>FR</td>
<td>387</td>
<td>Top plate buckled</td>
<td>57</td>
</tr>
<tr>
<td>FRa</td>
<td>162</td>
<td>Top plate buckled</td>
<td>34</td>
</tr>
<tr>
<td>FRb</td>
<td>212</td>
<td>Tube buckled</td>
<td>100</td>
</tr>
</tbody>
</table>

While buckling of the plate was the most prominent mode of failure, it is not representative of a typical mode of failure for this type of deck. The plates used in this case consisted of five layers which were not properly bonded causing premature local buckling as shown in Fig. 10. Buckling of the individual tubes is shown for Deck F2a in Fig. 11.

![Fig. 10: Plate Buckling in Deck F1](image3)

![Fig. 11: Tube Buckling in Deck F2a](image4)
Comparative Behaviour

Since all three of the prototype decks were given the same design characteristics (with the exception of Deck FR which incorporated a fibre mat wrap), it is important to compare their behaviour, shown in Fig. 12.

The three decks displayed the same stiffness during initial stages of loading. The deviation that occurred around 200kN was due to bar slippage, causing a sudden load drop. Certainly up to service load levels (140kN) and overall, the decks appear to behave similarly. This indicates consistent manufacturing and a reliable product.

![Fig. 12: Comparison of Behaviour Among Decks](image)

ANALYTICAL MODEL

Another component of the research is to establish an analytical model to predict the behaviour of the deck. Using Laminated Plate Theory (LPT), the effective stiffness of the composite element is determined (Mallick, 1993). A program was developed to perform such a task. The modulus of elasticity (E) and Poisson's ratio (ν) of both fibres and matrix, in addition to fibre volume ratio and fibre layering sequence were input into the program. LPT was used to determine an effective stiffness (E₁₁) for that element. In this way, an effective stiffness for the plates and the tubes of the deck was obtained.

![Fig. 13: Predicted vs. Actual Behaviour](image)

A program was developed to determine the overall stiffness of the deck itself based on its cross section properties. This program used the effective stiffness and dimensions of the separate elements of the deck (plates, tubes and bars) to calculate the stiffness of the entire composite section. A comparison of predicted (dashed line) to actual (solid line) behaviour for the deck designated FR is provided in Fig. 13.

The model appears to accurately predict deck behaviour, especially in the service loading range up to 140kN. With this model in place, it is now possible to adjust layering sequences and section dimensions and view their effects on deck performance. The
analytical model is used to design the second series of specimens, which is in progress at the time of writing this paper. Using the experience gained and the confidence established in the analytical model, the design process for the FRP deck will be optimized.

CONCLUSION

This paper introduced a new concept of a GFRP modular bridge deck. It detailed the patented fabrication process and discussed test results from the first prototype specimens. An analytical model is introduced to predict deck behaviour. This promising base of testing and good predictive model will allow rapid optimization of GFRP decks from the lab to widespread use in highway infrastructure.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the funds received from the Natural Sciences and Engineering Research Council of Canada (NSERC), the ISIS Canada Network of Centres of Excellence and the Industrial Research Assistance Program (IRAP), as well as the financial support, materials and collaboration provided by Wardrop Engineering Inc. and Faroex Ltd.

REFERENCES


