GFRP Modular Bridge Decks

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Abstract

Deterioration of concrete bridge decks has become a serious problem in recent years due to corrosion of steel reinforcement. There is also a need to replace existing bridge decks to accommodate the demand to increase the traffic load. The concept of using rapid deck replacement introduces an attractive approach which minimizes traffic interruption and consequently reduces replacement costs. This paper proposes an innovative fibre reinforced polymer (FRP) bridge deck as an excellent solution for infrastructure of highway bridges.

The proposed composite deck, patented by Wardrop Engineering Inc./Faroe Ltd., consists of a series of equilateral triangular section tubes produced by the filament winding process. Glass fibres are wound at varying angles, including fibres in the longitudinal direction, to achieve the target transverse and longitudinal strengths. The bridge deck consists of modules that are formed when several of the uncured, wound, triangular elements are placed between two pultruded plates and are subsequently cured into a single module of bridge decking. These modules are subsequently delivered to the site and within hours they are installed.

By virtue of the very materials and processes used, glass fibre reinforced polymer (GFRP) bridge decks offer high strength, lightweight and easy handling for installation. Most importantly, the absence of steel in the deck ensures that corrosion will never occur.

This paper provides a description of the deck, fabrication process and test results of a portion of the deck tested at the University of Manitoba. Prototype modules consisting of several tubes are tested in flexure under a simulated truck wheel load according to AASHTO specifications.

Popularity of this approach as an attractive alternative to conventional steel and concrete is evident by the fact that the National Composites Centre in the United States is planning to build over 100 composite bridges over the next 12 years.

Introduction

The highway infrastructure industry faces a large task ahead: the repair and replacement of thousands of highway bridges across North America. This challenge must be met with innovation and ingenuity in order to efficiently and economically prevent this infrastructure crisis.

There are several factors that have brought bridge structures to this critical point. It has been documented that over half of the United States’ 600 000 state, county and city bridges were built prior to 1940 [1]. Naturally these bridge decks are now reaching the end of their useful service lives. Second, the conventional materials of steel and concrete have proven to be susceptible to corrosion of steel rebar and consequently cracking of concrete caused by expansion of the steel volume. Finally, the heavy self-weight of concrete and steel has led to a reduced deck load capacity, yielding many decks to be inadequate for today’s standard truck load demands. This combination of material degradation and substandard load ratings has led to 200 000 US bridge structures being classified as deficient or functionally obsolete [1].

As an innovative alternative, this paper proposes the use of a fibre reinforced polymer (FRP) deck system. The bridge deck consists of modules

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constructed by bonding a number of glass fibre filament wound triangular tubes together and placing them between pultruded GFRP face plates. The advantages of FRP over conventional materials are discussed, and the manufacturing technique used to produce the prototype deck is provided. Finally, results from an initial deck test are presented and analysed.

Background

Problems with Current Materials
For years, steel and concrete have been the preferred building materials of civil engineers. Although they perform satisfactorily, use of these materials means dealing with a number of associated disadvantages.

Placement of steel reinforcement in the bridge deck can be an awkward job given the cumbersome nature of the material. Added to this are the many hours of labour required to prepare, cast and cure the concrete. Unfortunately, problems are not only limited to installation. Once in place, concrete is highly susceptible to any combination of attacks from moisture and chloride penetration to sulfate attack. All of these factors lead to cracking and spalling of the concrete, which only enhance the cycle of degradation.

While the concrete undergoes deterioration, the elements necessary for initiation of steel corrosion move in through the concrete cracks. Oxygen, water and chlorides react at the steel surface to corrode the rebar, reducing its cross section. As a result of the deterioration of the concrete and steel, the bridge deck can no longer be expected to resist the original loads for which it was designed.

This scenario is occurring all over North America: aging and deteriorating decks in need of repair or replacement. Clearly, the problem cannot be remedied by using the same materials that contributed to the problem in the first place. This is not using engineering technology to its full capacity. This paper proposes using a new and innovative material, which avoids all of these problems: FRP.

Advantages of FRP
FRPs consist of two components: fibres and matrix. The fibres possess a high modulus and strength, and are the main source of load resistance in any composite. The matrix is the medium in which the fibres are embedded, holding them in place and protecting them from harsh environmental conditions. More importantly, the matrix transfers the applied load to the fibres through shear force interaction. When the fibres and matrix are combined, the resulting composite possesses qualities superior to those of either component alone.

Due to their composition, FRPs have several advantages over conventional materials. First, they have a much higher tensile strength and modulus when compared with steel.

![Figure 1: Comparison of Stress-Strain Between GFRP and Steel Rebar [2]](image)

Another valuable quality of FRPs is that the low-density matrix makes for a lightweight composite. As a result of their low weight, FRP structural components are easier to handle, require less labour and can be installed rapidly. In the case of an FRP bridge deck, the end result is a reduced traffic delay on-site and lower installation costs overall.

A very significant advantage of FRPs is that they are virtually corrosion resistant. The matrix contains several chemicals which protect the fibres from most chemical and temperature aggressors. With a durable construction material, costly maintenance and repairs over the life of the structure are eliminated.

FRPs also offer design flexibility to the engineer. The wide range of composite manufacturing
processes available allows for a composite of almost any size or shape to be built. Thus, the demands and specifications of any number of civil engineering projects can be met easily with composites.

Finally, despite some prevalent perceptions, FRPs do have a proven reputation. They have been used successfully in the aerospace and boat manufacturing industries for the past 40 years [3]. This wide base of experience should provide civil engineers with the technical confidence necessary to use FRPs in structural applications.

Related Research
Despite the fact that the idea for composite bridges originated a short 20 years ago, a considerable quantity of research has been performed on the new technology. The research is focussed in several areas, but the main goal is to determine the most effective combination of deck geometry and manufacturing method to produce a cost-competitive deck. In addition to the cost issue, material and structural behaviour of FRP decks is also an aspect requiring much investigation. The importance of successfully reaching these goals cannot be emphasized enough. When FRP decks become cost-competitive with conventional materials, they will appear much more attractive to the engineering community. As well, with design codes and standards readily available to the engineer, the unease associated with using this new product will be overcome.

One of the leaders in GFRP deck research is DuPont Composites, who have studied a number of geometric deck configurations and loading conditions [4]. They have produced triangular and trapezoidal sections, as shown in Figure 2, using the Seeman Composite Resin Infusion Molding Process (SCRIMP). This process involves wrapping foam cores with off-the-shelf stitch-bonded glass fabrics, followed by infusion of the specimen with resin while under a vacuum.

The decks were tested in simply supported conditions under a single point load at the centre of their 2.4 m span. Decks with their cores oriented longitudinally consistently resisted a higher load (890 to 1220 kN) than those with transversely oriented cores (102 to 329 kN). Based on the test programme, it was suggested that triangular core specimens would be well suited to applications where the load path is primarily in one direction – which simulate the loading conditions of a bridge deck.

![Figure 2: Triangular and Trapezoidal Sections Produced by DuPont Composites [4]](image)

North Carolina State University has also produced and tested their own prototype of a GFRP bridge deck [1] with a cross section as shown in Figure 3.

![Figure 3: Section of FRP Deck Produced by North Carolina State University [1]](image)

The diamond and triangle cores were filament wound, then the structure was layed-up by hand. Unidirectional tapes were added at the end of the process to create a single deck unit.

When tested under fatigue loading, these specimens had minimal stiffness losses over 2 million cycles and 34% stiffness losses over 4 million cycles. When failure did occur, it was due to delamination between panels or between adjacent layers of different fibre orientations within the laminate.

Finally, West Virginia University and Creative Pultrusions have worked together to produce an FRP deck with a honeycomb shaped core using the pultrusion process [5], as shown in Figure 4.
Their research has progressed beyond the lab, to the point where they have constructed two 9 m long by 6.6 m wide modular GFRP bridges in West Virginia in 1997. To date, each bridge is performing very well, and both are resisting the AASHTO HS25 loads for which they were designed. Also, Martin Marietta Inc. joined with Glassforms Inc. in 1997 to install two GFRP bridges [3].

These demonstration projects are becoming more common and more numerous each year. Within the next 12 years, the National Composites Centre in Ohio, USA plans to build over 100 composite bridges [6].

Aiding in the progression from laboratory concept to real life application is the Market Development Alliance (MDA) FRP Composites Bridge team in the United States. This team is working to create documents of objective technical information consisting of standards, design codes and durability information, all of which will educate and familiarize engineering professionals with this new technology.

Proposed Innovative GFRP Deck: Experimental Program

Three prototype GFRP deck modules have been produced to date. The results of the first test are reported in this paper. The deck modules were designed by Wardrop Engineering Inc. and fabricated by Faroex Ltd. in Gimli, Manitoba. They were designed with the aim of resisting a truck load compatible with that of an HS30 AASHTO design truck. Testing was conducted at the W.R. McQuade Structural Lab at the University of Manitoba.

Deck Concept
The deck sample consisted of three triangular filament wound tubes, approximately 200 mm in height. The filament winding process was used because it is a relatively inexpensive process, and the material costs are considerably less than that of pultruded products.

The triangular tubes were bonded using wet resin from the filament winding process. Due to the rounded corners of the triangles, there was the potential for considerable voids at the top and bottom of the specimen. To eliminate weaknesses associated with this problem [7], pultruded GFRP bars were placed in the section. The specimen was fabricated using GFRP mat wrapped between the three tubes to provide resistance against interlaminar shear failure.

Finally, 15 mm thick GFRP plates were adhered to the top and bottom of the tubes to create one unit. The plates were made from GFRP laminates produced by Faroex. The plates consisted of five laminates stacked up and bonded, three in the longitudinal direction and two in the transverse direction. A schematic of the final cross section is provided in Figures 5 and 6.
the three triangular elements were then stacked on a pultruded plate and bonded by means of the uncured resin from the filament winding process. The GFRP mat was wrapped around the three tubes at this point, and the GFRP bars placed between the tubes to fill the voids. These steps are illustrated in Figures 9 and 10.

Figure 9: Wrapping Tubes with GFRP Mat

Figure 10: Placement of GFRP Bars as Filler

- The top face plate was laid on the section and bonded by added resin.

- Upon completion of assembly, the deck was wrapped and sealed in a plastic bag as seen in Figure 11.

Figure 11: Sealing Deck Module in Bag for Curing

Fabrication of Deck Samples

The process used by Faroex Ltd. to produce the deck samples can be summarized in the following steps:

- triangular shaped styrofoam mandrels were custom made, as shown in Figure 7. A thin layer of chopped fibres was applied to strengthen the mandrel surface.

Figure 7: Styrofoam Mandrels

- three 3.5 m long triangular mandrels were filament wound with Owens Corning Type 30 glass fibre rovings as seen in Figure 8. An eight layer laminate design was used, with a stacking sequence of [90 ±45 ±10 ±45 90]. Faroex used a custom-made epoxy resin with a 24 hour pot life.

Figure 8: Filament Winding Machine

- the three triangular elements were then stacked on a pultruded plate and bonded by means of the uncured resin from the filament winding process. The GFRP mat was wrapped around the three tubes at this point, and the GFRP bars placed between the tubes to fill the voids. These steps are illustrated in Figures 9 and 10.
the deck was then subjected to temperatures of 180°F for 8-10 hours, while a vacuum pump simultaneously worked to minimize air voids and remove excess resin in the deck. The final deck product (prior to cutting the specimen to desired length) is shown in Figure 12.

![Image: Final Deck Sample](Figure 12: Final Deck Sample)

**Testing**
The deck was tested under simply supported conditions, with a single point load of 250 mm x 250 mm applied at the centre of its 3 m span. This load simulated the wheel load of a truck. At both the supports and the central loading point, neoprene pads of 15 and 25 mm thickness, respectively, were used. The test setup is provided in Figure 13.

![Image: Test Setup](Figure 13: Test Setup)

The load was applied by a closed-loop 1000 kN MTS loading machine using stroke control at a rate of 0.75 mm/min.

Deflections were measured using linear variable differential transducers (LVDTs) located at midspan and at one of the supports. The latter measurement was made to determine settlement of the neoprene pads in order to obtain the net midspan deflection.

**Results and Discussion**

**Failure Mode**
The deck specimen failed due to delamination of the bottom plate in tension from the tubes. The plate completely delaminated from the tubes at midspan as shown in Figure 14.

![Image: Delamination of Bottom Plate](Figure 14: Delamination of Bottom Plate)

At the ends of the beam, however, failure was marked by a significant degree of slip between laminas of the lower plate. It was observed that the bond between the triangular tubes and the plate was preserved while the interlaminar bond in the plate failed, as illustrated in Figure 15. This delamination failure occurred at a load of 414 kN.

![Image: Plate Slip at End of Beam at Failure](Figure 15: Plate Slip at End of Beam at Failure)

**Load-Deflection Behaviour**
The load-deflection curve measured from the test is shown in Figure 16.

Upon unloading at a load level of 50 kN and reloading the deck, it was observed that the deck resumed its original stiffness without permanent deformation. At a load of 200 kN it was observed that the GFRP bars slipped a distance of about 1 cm, causing a sudden drop in load carrying capacity. The bar slip at failure is shown in Figure 17. Although not affecting the load-
deflection curve, the uppermost ply of the top plate suffered local buckling at 300 kN. Finally, at 414 kN the deck failed due to delamination of the bottom plate as described earlier.

Figure 16: Load-Deflection Behaviour

![Figure 16: Load-Deflection Behaviour](image1)

Figure 17: Bar and Plate Slip at End of Beam

The maximum measured deflection that the deck experienced was 69 mm at midspan.

**Strain Behaviour**

The following figure depicts the axial strain behaviour as measured at the face of the specimen midway between midspan and the supports. The results show that the plates experienced slightly higher strains than the tubes, however both elements displayed linear behaviour. The measured strain for the same section at ultimate is also shown in Figure 18. Once again, a very linear distribution was obtained, verifying the linear properties of glass fibre composites.

![Figure 18: Axial Strain Behaviour](image2)

Figure 19: Axial Strain Distribution Along Bottom Plate

Overall, the maximum tensile strain reached was 0.0097 along the centreline of the lower plate, directly beneath the applied load. The maximum measured compressive strain attained was −0.0049 located 300 mm diagonally away from the central loading point where the maximum strain was expected. This maximum was reached at this location due to the local buckling of the upper plate.

![Figure 19: Axial Strain Distribution Along Bottom Plate](image3)

**Conclusions**

This paper introduced the concept of a GFRP modular bridge deck. This new innovation holds a number of advantages over conventional concrete and steel, including lightweight, durability and ease of installation. This paper also reviews several similar research projects in the
US, proving the growing popularity of the FRP approach. The unique processing method used by Faroex Ltd. was described, and test results from one prototype deck provided. Based on the preliminary test results, this new technology holds much potential for widespread use of the proposed innovative system for highway bridges.

Future Work

There are several areas which must be researched before FRP bridges can be installed on a regular basis. The authors are constantly modifying the production technique to create a more repeatable, cost-efficient process. Lower cost in comparison to other conventional materials will allow composite bridges to break through the market and compete with the conventional materials such as concrete and steel. Ongoing research is currently in progress to establish models capable of predicting the behaviour of composites. With the behaviour documented and capable of being predicted, design standards and codes will be provided. This base of reliable information will provide the confidence and reputation necessary for the widespread use of FRP bridges in highway infrastructure.

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