STATIC BEHAVIOR OF HYBRID FRP-CONCRETE BRIDGE SUPERSTRUCTURE

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ABSTRACT

In this study, the concept of the hybrid FRP-concrete design was exploited in a new type of bridge superstructure system. The proposed hybrid superstructure was designed as a simply supported, single-span, one-lane bridge with a span of 10 m. The bridge superstructure consists of two bridge decks and each deck is comprised of four fiber reinforced polymer (FRP) box sections combined with a thin layer of concrete in the compression zone. This new design was proposed to reduce the initial costs and increase the stiffness of FRP composite structure. This paper presents the results from the experimental study on a one-third scale model of the hybrid FRP-concrete bridge superstructure. The scale model was subjected to four-points loading to simulate the truck load. The test results indicate that the proposed bridge model meets the stiffness requirement and has significant reserve strength.

KEYWORDS

FRP, concrete, hybrid structure, bridge superstructure, bridge deck.

INTRODUCTION

A major concern for many bridge superstructures is the significant reduction in durability and life expectancy caused by the corrosion of the reinforcing steel and the corresponding deterioration of the concrete. These problems are accelerated by the application of de-icing salts in cold area. The corrosion will eventually cause enough damage to warrant a superstructure replacement or retrofit (Robbins 2002). According to the U.S. National Bridge Inventory, nearly 27 percent of 590,000 public bridges were either structurally deficient or functionally obsolete as of 2003. The U.S. Department of Transportation (DOT) estimates the average annual cost to improve bridge conditions for the 20-year period of 1998-2017 to be $10.6 billion in 1997 dollars (Kitane 2004). The similar situation exists in China. These facts imply that it is imperative to develop and construct bridge systems that have long-term durability and require low maintenance.

As one of the solutions to this problem, structural applications of fiber reinforced polymer (FRP) composites have recently been attractive in the civil engineering community due to their superior material properties such as high corrosion resistance, high specific strength, and high specific stiffness. In terms of initial costs, FRP composites are still too expensive to compete with other conventional materials used in civil engineering applications. To make the best use of materials and reduce the initial costs, combinations of FRP and conventional materials have recently been investigated by a number of researchers (Keller et al. 2007). The advantages of the combined or hybrid structural systems include the cost-effectiveness and the ability to optimize the structural section based on material properties of each constituent material. According to Mirmiran (2001), the most effective use of FRP composites in civil structural applications is in the form of a hybrid construction with concrete.

Among the bridge maintenance items at U.S. DOT, bridge decks are ranked No.1 maintenance priority (Kitane 2003). Therefore, the concept of the hybrid FRP-concrete structural system was applied to bridge superstructure in this study. The primary objectives of this study were to propose a conceptual design of a hybrid FRP-concrete bridge superstructure, and to examine its performance under live loads by experimental investigation.

PROPOSED HYBRID FRP-CONCRETE BRIDGE SUPERSTRUCTURE SYSTEM

Although many configurations of the hybrid FRP-concrete bridge superstructure are possible, a conceptual design of the hybrid bridge superstructure shown in Figure 1(a), where supports and substructures are not shown, was chosen. A prototype bridge was designed as a simply supported, single-span, one-lane bridge with a span
length of 10 m. Geometrical parameters of the cross sections in Figure 1(b) were determined based on numerous finite-element analyses. The cross section of the bridge is comprised of 8 box sections, each of which has a layer of concrete in the compression zone. E-glass woven fabric reinforcement and vinyl ester matrix were selected as constituents for the GFRP laminate. In this study, the ratio of the area of concrete to the total area in the cross section is 0.4.

The bridge design is based on the traditional plank bridge concept, in which a number of individual beams are placed side by side to create a bridge. The advantages of this concept include: (1) corrosion resistance for steel-free design; (2) initial costs reduction due to the effective use of concrete; (3) lightweight; (4) reduction of local deformation under concentrated loads that is found to be a problem in all-composite bridge; (5) no joints between decks and girders (the girders are the decks); (6) significant understanding of the bridge behaviour can be obtained by testing of individual beams; (7) the concept is well understood by bridge engineers.

Four beams make up a bridge deck with a width of 2,040 mm. The prototype bridge consists of two bridge decks. The 2,040mm wide bridge deck can be easily transported to site on a standard truck and assembled into a bridge using simple field joints.

The design concept is similar to the concept proposed by Van Erp et al. (2002). However, there are several distinctnesses, including: (1) without utilization of CFRP due to its expensive price and lack of source in recent years in China; (2) usage of normal concrete instead of polypropylene fiber reinforced concrete; (3) the ways of assembling between two decks, and among GFRP beams in the bridge deck.

EXPERIMENTAL PROGRAM

Materials

Two types of bidirectional E-glass woven fabric with a weight of 600 g/m², (0°/90°) and (±45°), were selected as the primary continuous reinforcement of FRP laminates. In these fabrics, fibers in 0° and 90° or +45° and -45° directions have the same weight (300 g/m²). Vinyl-ester resin, Swancor 901, was chosen as the matrix. Vinyl-ester resins are typically used when high durability, thermal stability and extremely high corrosion resistance are required; therefore, they are very suitable for civil engineering structures.

Due to the size of the test specimen, coarse aggregates with maximum size of 10 mm were used in the concrete. The compressive strength of the concrete on the day of test is 62 MPa. Young’s modulus of the concrete will be slightly smaller than the normal concrete due to the use of small size coarse aggregates.

Test Specimen

The test specimen is a one-third scale model of the 10 m hybrid FRP-concrete bridge superstructure shown in Figure 1. As mentioned above, the bridge superstructure consists of two same bridge decks. Figure 2 shows the cross section of a scaled bridge deck. The specimen (FRP part only) was fabricated at Harbin Composites Corp. of China. The box sections were fabricated by the hand lay-up process at present stage. The top flange and the webs of each box section had the same fiber architecture, which consisted of 12 layers of woven fabric reinforcement. However, the bottom flange consisted of 18 layers of woven fabric to increase the global stiffness of the section. Stacking sequences of the top and bottom flanges were [(0°/90°)3, (±45°)2, (0°/90°)]s, [(0°/90°)3, (90°/0°)3, (±45°)2, (0°/90°)]s, respectively. The fiber volume fraction of the FRP part is about 0.3.

The eight individual box beams were fabricated firstly. Secondly, by combining two sets of 4 box beams each using vinyl-ester resin and chopped strand mat (CSM), 2 sections with a width of approximately 680 mm were created. Thirdly, the two sections were wrapped individually with a laminate having a [(0°/90°)3], laminate construction to strengthen the transverse stiffness of the sections. Fourthly, concrete was cast on the top surfaces of the two sections, forming the hybrid FRP-concrete bridge decks (shown in Figure 2). Finally, the 2 bridge decks were assembled together, forming the proposed hybrid bridge superstructure (shown in Figure 1). The connecting details for the 2 bridge decks are shown in Figure 3. High quality vinyl-ester resin and CSM were also used to bond the FRP parts (webs). Mortar/epoxy mortar was selected to fill the prepared gaps of the bridge
decks. And FRP rebar was adopted to fill the gap at the bottom surface of the bridge superstructure. Additional FRP laminate was added to the bottom of the bridge superstructure to give the structure some transverse stiffness. In real bridge assembling, FRP layer and FRP rebar will be neglected for simple operation.

To develop a good bond between FRP part and the concrete layer, 5~10 mm fine aggregate was applied to the top surface of FRP part with epoxy adhesive. Applying too much or too little aggregate could create insufficient bond between FRP and concrete for the two materials to act compositely. The aggregate distribution percentage was recommended to be 35%~45% to obtain the optimal bond (Berg 2004).

**Test Setup and Apparatus**

The test setup is shown in Figure 4. Loads were applied vertically at four points on the top surface of the test specimen by three spreader beams and the screw jack supported by the top beam of a reaction frame. The load configuration simulates the two heaviest axles of the standard truck load (total 5 axles) specified in the Chinese Bridge Design Specifications (JTG D6-2004). In the specifications, the design truck load is a live load and has 5 axles. And the two heaviest axles are specified as 140 kN each, where one axle is 1.4 m away from the other. Each axle has two tires that are 1.8 m apart center-to-center, and each tire area has a length of 0.6 m and a width of 0.2 m. For the 1/3 scale model, this design truck load becomes two axles of 31.11 kN, 0.467 m apart. Two tires of each axle are 0.6 m apart, and each tire area is 0.2 m long and 0.067 m wide.

The test specimen was simply supported by concrete blocks with a support length of 0.2 m at each end. Rubber pads were used to protect the bottom surface of the specimen from damage. Figure 5 shows the positions of the displacement and strain measurement to be acquired during the experiment. Only longitudinal strain was selected to be measured in the study. Since the joint that lies justly on the centreline of the specimen is relatively weak, the strain measurements along the centreline mentioned below have to deviate slightly from the real centreline of the specimen to avoid the joint.
Test Procedures

The hybrid FRP-concrete bridge specimen was tested by flexural and off-axis flexural loadings (shown in Figure 6) firstly. These tests were performed by force control, and the maximum load of 3 times the scaled truck load (93.3 kN) was applied. In the tests, displacement and strain were measured. Then the hybrid bridge model was tested in flexure to failure to examine its ultimate strength and failure modes. The strength test was also performed by force control, and it was divided into two steps. In the first step (Step I), a cyclic force profile was used with the amplitude gradually increased. For each cycle, the force ranged from 0 to a predetermined amplitude, and three cycles were applied for each amplitude to examine the deflection stability. In the second step (Step II), force was increased monotonically until the test specimen failed.

**Figure 6. Loading configurations (dimensions in mm)**

**TEST RESULTS AND DISCUSSIONS**

**Flexural Test**

No sound of cracking of either the concrete or GFRP was heard during the flexural test. Visual inspection after the test revealed no cracking in the surface of the test specimen. Figure 7 shows the force-displacement relationship obtained at E-C (see Figure 5 for the location). It can be concluded that the obtained force-displacement response is very much linear and has a good repeatability for the hybrid bridge specimen. The deformed shapes of the bottom surface are described in Figure 8. From this figure, we can see that the deformed shapes of bottom surface at midspan section (section E) are nearly linear, which indicates that the hybrid bridge specimen has adequate transverse stiffness and the 8 box beams can work together as a plate.

**Figure 7. Force versus displacement at E-C (flexural test)**

**Figure 8. Deformed shapes of bottom surface at section E (flexural test)**

**Figure 9. Longitudinal strain obtained at bottom and top center (flexural test)**

**Figure 10. Longitudinal strain obtained on exterior web at section E (flexural test)**
It is specified in the Chinese Bridge Design Specifications (JTG D6-2004) that the maximum deflection under live loads is smaller than \( L/600 \) (\( L \) = span length). The live load for this check is design truck load. As the span length of the test specimen is 3.333 m, the maximum deflection under truck load has to be smaller than \( L/600 = 5.555 \) mm. Deflection due to truck load measured at E-C is 2.16 mm = 0.39\( \times \frac{L}{600} \). The hybrid bridge specimen well satisfied the Chinese live load deflection specification.

Longitudinal strain variations along the centerline of the bottom and top surface and over the height on the exterior web are shown in Figures 9 and 10. Figure 9 shows that longitudinal strain variations along the centerline of the bottom and top surface appear to have a good regularity with the expected results. Figure 10 shows that the bending theory for small strain can apply — i.e., the plane section before deformation remains plane after deformation. And the concrete layer is in the compressive zone, which is designed to utilize concrete effectively.

Off-Axis Flexural Test

The screw jack and spreader beams were then moved off the centreline by 167 mm, so that the jack could apply an off-axis load, as shown in Figure 6(c). 167 mm was the largest eccentricity in the real traffic condition. Applied load history was the same as that used for the symmetrical flexural test. No sound of cracking of either the concrete or GFRP was heard during the experiment. Visual inspection after the test revealed no cracking in the surface of the test specimen. The obtained deformed shapes of the bottom surface are shown in Figure 11. Eight box sections acted together under such a load and the bonding between box sections was strong enough to keep them together. This design appears to have excellent section torsional resistance.

Strength Test

Figure 12 shows force-displacement responses obtained at E-C during the strength tests (Step I and II). At the load of near 16\( \times \)truck load in step II, there was a medium loud noise. It is regretted that visual inspection was not conducted in time. So the noise may be caused by the cracking of the interface between FRP and concrete or the cracking of concrete under the loading points. And at this point, the slope of force-displacement curve changes slightly. The load was 8.8 times the Chinese Bridge Design requirement of 1.4\( (1 + IM) \)\times\)truck load for live loads in the strength limit state, where \( IM \) = dynamic load allowance, and has a value of 0.3 in this case. The load path from Step II shows that the loading path is nearly linear until the specimen failed. A global failure as shown in Figure 13 occurred at 28\( \times \)truck load, which is 15.4 times the 1.4\( (1 + IM) \)\times\)truck load. Crushing of concrete in compression near the loading points defines flexural collapse of test specimen. However, the FRP part was found to be intact. This can be described as follows. As concrete failed, large deflection occurred immediately due to the low stiffness of FRP part in comparison to the hybrid specimen, along with instantaneous reduction of the load for the quick increase of deflection, and the combined compression capacity of the FRP top flange and the residual strength of the concrete enable the specimen to carry the residual load. After unloading the residual load, the deflection of the specimen almost came back. The failure was sudden due to the nature of the concrete. However, the obtained failure mode is considered to be favorable because it did not lead to collapse of the entire bridge and the bridge can be retrofitted easily by the replacement of the concrete layer. As pointed out by the Chinese road authorities, trucks in excess of many times the legal limit have been detected in China. These extreme loads can initiate cracks or cause damage in a bridge structure, which may propagate...
under subsequent dynamic load, resulting in a significantly decreased life span. However, the proposed bridge model has significant reserve strength. It will be very beneficial for the ubiquity of overload operation in China.

![Loading point](image)

(a) Top view (b) Side view

Figure 13. Failure of test specimen

CONCLUSIONS

The experimental study presented here shows the feasibility of the proposed hybrid FRP-concrete bridge superstructure. The main features of the proposed design include: (1) the efficient use of the concrete layer in the compressive zone to increase the system stiffness, and to reduce the FRP composites and initial costs; (2) the effective implementation of fine-aggregate coating to ensure composite action between the FRP and concrete; (3) the effective ways of assembling between two decks, and among FRP box beams in the bridge deck; and (4) the use of box sections to provide significant torsional stiffness for the cross section.

As is often the case with FRP composite bridges, the design of the proposed bridge superstructure is stiffness-control. It has been proved that the proposed hybrid bridge can be designed to meet the live load deflection requirement of Chinese Bridge Design Specifications and to have significant reserve strength (15.4 times design requirement for scaled specimen). Therefore, the depth of the bridge may be increased so that the same flexural rigidity can be achieved with less material and the strength can be used more efficiently.

The concept of the hybrid design—using different materials where they perform best—is a very prudent way to design a structure. A combination of FRP composites and concrete is especially promising in civil infrastructure applications. Although the proposed hybrid FRP-concrete bridge superstructure may not be close to an optimal design, it gives an example of the hybrid design in a bridge superstructure application.

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