Review of Bridge Decks Utilizing FRP Composites in the United States

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Abstract

This paper deals with the development, production and testing of different types of bridge decks utilizing FRP composites. The bridge decks discussed herein (concrete deck with FRP rebars; all FRP composite Hardcore Deck, H-Deck, Kansas Deck, MMM Deck and Cellular Deck) incorporate several different FRP composite bridge deck designs developed in the United States. A bridge utilizing FRP composite rebars in concrete deck is discussed first; followed by discussion of all FRP composite bridge decks. The information for each bridge system is summarized from referenced publications.

Laboratory and field tests indicate that the bridge decks utilizing FRP composites are performing well. All FRP composite bridge decks are about five times lighter than concrete bridge decks. Other features of all FRP composite bridge decks are that they: (1) are well suited for modularization and mass production; (2) posess good energy absorbing capacity; (3) have enhanced fatigue and corossion resistant properties; and (4) require less erection time in the field since they are light-weight and use light equipment. At present, the higher initial cost of bridge decks utilizing FRP composites is an obstacle for their acceptance by bridge engineering community. The cost of bridge decks utilizing FRP composites will decrease as the demand increases, resulting in higher volume of production.

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Introduction

Fiber Reinforced Polymer (FRP) composite materials have advanced over the years to be used for many different applications including aerospace, automotive, off-shore and highway structures. FRP materials are light-weight compared to conventional materials and more forgiving in terms of corrosion. These advantages have resulted in strucural engineers designing rebars, tendons, sheets, laminates, wraps, shells, and structural shapes that can be used in bridges. This paper deals with the development, production and testing of different types of bridge decks utilizing FRP composites. The bridge decks discussed herein (concrete deck with FRP rebars; all FRP composite Hardcore Deck, H-Deck, Kansas Deck, MMM Deck and Cellular Deck) incorporate several different FRP composite bridge deck designs developed in the United States. Bridges utilizing conventional and FRP products are discussed first; followed by discussion of all FRP composite bridge decks. Issues that are discussed for each system are stiffness and strength, transverse load distribution factors and connections.

Concrete Deck Reinforced by FRP Bars

The Northern Panhandle of West Virginia at McKinleyville is the home of the first vehicular bridge in the United States to use FRP reinforcement in a concrete deck (Figure 1). The bridge is the outcome of ten years of research conducted by the Constructed Facilities Center-West Virginia University in cooperation with the United States Army Corps of Engineers, the Federal Highway Administration, and the West Virginia Department of Transportation-Division of Highways.

Production: The selection of constituent materials and the manufacturing processes for FRP rebars were given careful consideration. Screening of several types of resins and fibers was researched in cooperation with Reichhold Chemicals. The screening included exposing FRP rebars to alkaline and salt environments under ambient, freeze-thaw temperatures and sustained stress. Two types of rebars, C-bars and sand-coated bars were used in this deck. The C-bar is constructed of continuous E-glass fibers with a polyester resin core, combined with a shell comprized of compression molded chopped E-glass fibers and urethane-modified vinyl ester compound. The sand-coated bars consist of E-glass fibers and isophthalic unsaturated polyester resin. The pultruded bar was then wrapped with two additional fiber chords in a helical pattern and coated with a layer of epoxy resin, and finally rolled in sand. The sand coating is intended to provide a better mechanical bond with the surrounding concrete (Thippeswamy et. al., 1998).

Construction: The first stage of construction of the bridge deck involved the layout of the FRP bars. The construction crew handled the FRP rebars similar to the way steel rebar would be handled. To minimize the difference in the installation procedures, plastic coated steel wires were used to tie the bars together. A concern of the FRP rebars was that they are more flexible than steel rebars under the weight of the construction equipment and crew. Epoxy coated steel chairs were placed to support FRP rebars (spaced at 1.2 m) in both the transverse and longitudinal directions, thus, limiting excessive flexing of FRP rebars under the weight of the construction equipment and crew. Another concern was the flotation of FRP rebars in wet concrete due to their (FRP rebars) density being lower than wet concrete. To overcome the problem, the FRP mesh was tied down at regular intervals to the form-work using plastic coated steel wires.

Field Test: McKinleyville bridge is a 54 m (177 ft) long, three span, continuous integral abutment bridge accommodating two lanes of traffic. The bridge was load tested after construction (before opening to traffic) and during service. The maximum live load was simulated using three trucks, two weighing about 245 kN (55 kip) and a third weighing about 120 kN (27 kip). The trucks were positioned to induce the maximum positive and negative bending moments for the three span bridge. The maximum strain observed in the FRP rebar was 275 microstrains which corresponds to a stress of about 11.5 MPa (1.7 ksi). This stress if prorated for HS-25 truck loading including impact, results in an approximate value of 18 MPa (2.6 ksi). The observed stress is about 3% of the ultimate tensile strength [560 MPa (80 ksi)] of the FRP rebar. However, the observed stress doesn't take into account the dead load induced stresses or effects of material property degradation due to aging. Deflections were measured for the three spans on the steel stringers and the concrete deck. Observed maximum superstructure deflection of 9 mm, for positive bending case under HS-25 truck loading including impact, corresponded to a value of span/1500. Observed maximum deck deflection of 0.25 mm, when the wheels were placed at the mid-span of the deck (between two interior stringers) was very small. Transverse load distribution factors were calculated at the maximum deflection location and they are about the same as those for steel reinforced concrete decks.

FRP Composite Deck Over Post-Tensioned Concrete Edge Girders

In June of 1997, a 22 m long by 6 m wide, single span, simply-supported bridge was erected over Magazine Ditch in Delaware. The bridge consists of a GFRP deck that distributes transverse loads to traditional post-tensioned concrete edge girders (Chajes et. al., 1998). The Magazine Ditch bridge is a result of a collaboration amongst the University of Delaware, Hardcore DuPont Composites, J. Muller International, Anholt Technologies, the Federal Highway Administration, and the Delaware Department of Transportation.

Production: The process used to fabricate the prototype was Vacuum-Assisted Resin Transfer Molding (VARTM). The process requires minimum tooling and, therefore, can be used to fabricate large deck panels. The VARTM prototype molds use foam as tooling to mold the cells. In the VARTM process, the fabrics are laid up dry by hand, then a vacuum is applied and resin is infused. In this process, the product uniformity is difficult to maintain resulting in high dimensional variations. The fabric used is a heavyweight multiaxial stitched fabric with chopped strand mats.

Laboratory Test: Component tests as well as full-scale deck tests (1.2 m long by 6 m wide) were performed by the University of Delaware researchers. These tests included applying AASHTO service loads, as well as subjecting the deck to fatigue cycles. The fatigue tests indicated negligible loss in strength and stiffness of the GFRP deck (Chajes et. al., 1998).

FRP Composite Honeycomb Deck

Kansas Structural Composites Inc., has designed, fabricated, proof tested and deployed an all composite bridge over No-Name Creek in Russell, Kansas. The deck is comprised of a thin layer of polymer concrete covering two layers of alternating laminates of chopped strand mat and uniaxial fibers. The top and the bottom laminates sandwich FRP honeycomb core.

Production: The honeycomb core was fabricated on existing corrugated molds. The faces were hand laid up and the panels assembled on a 3 m x 7.3 m (10 ft. x 24 ft.) platen constructed of steel tubing and particle board.

Laboratory Test: A test specimen with a clear span of 2.13 m by 30.5 cm (7 ft by 12 in) was tested under three and four point loads. Three series of loads were applied under each loading condition. The first series in each case was used to settle the beam and the equipment. Table 1 exhibit the results of the third series of test in terms applied load versus flexural rigidity (D), shear modulus (G) and modulus of elasticity (E) values determined. Table 1 reveals increase in beam stiffness with the load increase. This phenomenon is most likely due to increased load sharing by fibers in the faces, in addition to load sharing by the honeycomb core. Bending and stretching interaction of a plate also enhances the plate stiffness. The beam was not tested to failure, but surpassed the wheel load specifications for AASHTO loading (Plunkett, 1997).

Field Test: The Kansas Deck was installed over No-Name creek in Russell, Kansas in October 1996. The bridge consists of three deck panels, each measuring about 2.75 m (9 ft) by 7.1 m (23.3 ft) by 0.56 m (22 in). At the intersection of the panels, one section is installed with flanges facing outward to form a receptacle for the adjoining panel to fit inside with its male counterpart. The overall dimensions of the bridge are 6.48 m (21 ft 3 in) by 8.03 m (26 ft 4 in). The load test conducted in November of 1996 consisted of placing two fully loaded dump trucks on the deck at pre-designated locations. The first Truck (Truck A) weighed 186.4 kN (41.9 kip) on the rear tandem axle and the second truck (Truck B) weighed 189.4 kN (42.58

kip) on its rear tandem axle. Dial indicators were placed on the mid-span at the north and south edges, at the centerline, and at the two joint panels. For test 1, truck A was placed on the center of the south lane at the center of the span and deflections were recorded. For test 2, truck B was then placed on the center of the north lane at the center span and deflections were recorded with both trucks on the bridge. Next, for test 3, truck A was removed from the bridge and the deflections were recorded for truck B. The larger deflections on the north edge can be partially due to the placement of the second truck closer to the edge of the bridge. Also, the second truck B carried slightly higher load than truck A. The maximum deflection of 4.60 mm (0.181 in) with an applied load of 375.79 kN (85 kip) yielded a span/deflection ratio of 1450 (Plunkett, 1997).

FRP Composite H-Deck (Superdeck™)

The Constructed Facilities Center-West Virginia University, the Federal Highway Administration, the West Virginia Department of Transportation-Division of Highways and Private Industries, have worked cooperatively to laboratory test and field test several FRP composite structures. The researchers have designed and developed a new FRP composite structural shape called the H-Deck (Superdeck™).

Production: The H-Deck is manufactured by Creative Pultrusions, Inc. through standard pultrusion process. Creative Pultrusions, Inc. fabricated two dies, one for double trapezoid component and the other for the hexagonal component. Figure 2 shows the picture of the H-Deck being installed on steel beams.

Laboratory Test: Static load test followed by fatigue tests were conducted on the H-Deck specimens (Howdyshell et. al., 1998). The simply supported specimen dimensions were 2.74 m (9 ft) long by 0.914 m (3 ft) wide. Intermediate static load tests were conducted at every 0.5 million fatigue cycles up to 2 million fatigue cycles at 3 Hz. The load range for fatigue test was 8.9 kN to 155.7 kN (2 kips to 35 kips). The loss of stiffness at the end of 2 million fatigue cycles was less than 4 percent. Further, Static failure tests were also preformed on two H-Deck specimens (one H-Deck was fatigued to 2 million cycles and the other H-Deck had no prior load history) using the same setup as in the fatigue test. The results (Table 2) of the two tests indicated that the strength of the H-Deck exceeded the live load for AASHTO-HS25 loads and the deck met a L/500 deflection criterion for a 9 ft. span.

Field Test: The H-Deck was installed at two sites in West Virginia, two sites in Ohio and one site in Pennsylvania. The first bridge in West Virginia at Laurel Lick is an all FRP composite structure consisting of FRP composite H-Deck, FRP composite WF beams, FRP composite piles and FRP composite cellular panels used as a filler between piles. The wearing surface over the FRP deck is a thin polymer concrete. The second bridge in West Virginia Wickwire Run Bridge (Figure 2) consists of the H-Deck on conventional steel beams. The length and width for the

Laurel Lick and Wickwire run bridges are 6.1 m by 4.9 m (20 ft by 16 ft) and 9.14 m by 6.61 m (30 ft by 21.7 ft), respectively.

The Wickwire Bridge consists of three H-Deck modules resting on four steel WF beams that are supported by concrete abutments. The deflection equipment was placed on the bottom flange of each of the steel beams and the mid-span of the deck between beams. First load case consisted of placing the rear axle of a loaded dump truck at the center of the bridge to induce maximum global (beam) deflection. Second load case consisted of placing one set of wheels at mid-span of the deck between two interior beams to induce maximum local (deck) deflection. The maximum local (deck) deflection, when prorated for HS-25 live load plus impact, yielded a span/deflection ratio of 1000. Transverse load distribution factors were determined for the H-Deck from measured deflections. The factors were also theoretically established using modified orthotropic plate theory (GangaRao, et. al., 1975). A good correlation was obtained between the theoretical and experimental transverse load distribution factors.

Fully Instrumented Composite Bridge (Tech 21 Bridge)

The bridge deck that Martin Marietta Materials (MMM) developed was field implemented in Butler County, Ohio, in July of 1997.

Production: The woven glass fabrics are folded and formed to the desired structural shape, impregnated with isopolyster resins and drawn under heat and pressure through a pultruder. In addition, layers of fabric/resin are laminated in various thickness and form to create extremely strong face sheet. The component shape and face sheet are then assembled through the use of adhesives to construct bridge decks. The Tech 21 bridge deck is fabricated using three panels. The panels are connected with the use of an adhesive bond and can be attached to the supporting beams using blind bolts and Nelson studs.

Field Testing: The Tech 21 Bridge is 10 m long by 7.32 m wide (33 ft by 24 ft). Initial field test indicated the load capacity of the bridge exceeded AASHTO loads by more than a factor of two. The Tech 21 Bridge is the first fully instrumented bridge in the United States. This bridge has special sensors embedded within the deck that are linked to a system of computers for continuous monitoring.

FRP Composite Cellular Panel for Pedestrain Bridges

The researchers at the Constructed Facilities Center (CFC) of West Virginia University worked cooperatively with the Federal Highway Association and Creative Pultrusions, Inc., to develop a fiber reinforced cellular deck system.

Production: The structural shape selected for the deck research was rectangular multi-cellular panel pultruded from E-glass fabrics and polyester resin. Wide flange H-sections were selected to connect the cellular panels.

Laboratory Test: After completing the investigation of the behavior of FRP structural shapes and their joints at coupon and component levels, a series of experiments was conducted on a FRP cellular deck-steel beam system composed of the previously tested shapes and joints. Static tests were performed under AASHTO HS-20 design loads. The bridge model consisted of a 2.4 m wide by 4.9 m long FRP cellular deck supported on three steel stringers spaced at 1.09 m apart. The bridge was instrumented to obtain the deflected shape of the deck and beams. Concentric, double-symmetric, and eccentric loads were applied to the bridge system. Table 3 gives maximum beam deflections for a simply supported test specimen at a span of 4.57 m. Local deck deflections for the double-symmetric and off-center load cases, at stringer spacing equal to 1.09 m, are given in Table 4. The above values of local deck deflections were the average of the net deck deflections at each cell of the bridge system. Table 4 presents that the addition of stiffeners in the cells of the loaded panel decrease the total and net deflections of the deck at mid-span. Load distribution factors (LDF) were also calculated for each of the three beams based on the experimental deflection readings. The LDF factors show that the middle stringer carried most of the load when symmetric loads were applied. In the eccentric case, the load was mostly distributed to the stringers under the load patches. The deck is very economical and can be used for pedestrian bridges only.

Conclusions

Three major types of bridge deck systems are presented in this paper. The first type is concrete bridge deck with FRP rebars; the second type is all FRP composite bridge deck; and the third type is all FRP composite pedestrian bridge deck. In the second type, two of the decks were fabricated using a pultrusion process (H-Deck and MMM Deck), the VARTM method was used to fabricate the Hardcore Deck, and hand lay-up techniques were used to construct the Kansas Deck. The third type of deck system is a light weight, highly economical FRP composite cellular deck fabricated using pultrusion process. This type of deck is ideal for pedestrian bridges.

Laboratory and field tests indicate that the bridge decks utilizing FRP composites are performing well. All FRP composite bridge decks are about five times lighter than conventional concrete bridge decks. The average weight of an all FRP composite deck is about 20 lbs/ft^2 compared to a conventional concrete bridge deck weight of 110 lbs/ft^2. Other features of all FRP composite bridge decks are that they: (1) are well suited for modularization and mass production; (2) posess good energy absorbing capacity; (3) have enhanced fatigue and corossion resistant properties; and (4) require less erection time since they weigh less and use light equipment.

At present, the higher initial cost of bridge decks utilizing FRP composites is an obstacle for their acceptance by bridge engineering community. The cost of H-Deck (first generation Superdeck™) is approximately $2.25 per pound, resulting in about a square-foot cost of about $50 to $55. The cost of bridge decks utilizing FRP composites will decrease as the demand increases, resulting in higher volume of production.

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Load (lb)	D (lb-in^2)	E (psi)	G (psi)
20,000	9.4×10^8	4.3×10^5	5.1×10^4
25,000	9.9×10^8	4.5×10^5	3.7×10^4
30,000	10.0×10^8	4.8×10^5	3.0×10^4

Table 1. Stiffness Properties of Lateral Test Beam (Plunkett, 1997)

Specimen Type	Max. Deflection	Maximum Load
Fatigued Deck (2 Million Cycles)	39.1 mm (1.54 in)	553.8 kN (124.5 kips)
New Deck (No Prior Load History)	39.9 mm (1.57 in)	563.59 kN (126.7 kips)

Table 2. H-Deck Failure Test Results (Howdyshell et. al., 1998)

Loading Type	Design Load (kN)	Max. Deflection (mm)	Deflection/Span
Concentric	145	7.85	1/582
Double Symmetric	193	7.62	1/600
Eccentric	193	8.77	1/521

Table 3. Maximum Beam Deflections in Cellular Panel-Steel Beam System (Sotiropoulus, 1995)

Loading Type	Design Load (kN)	Max. Deflection (mm)	Deflection/Span
Double Symmetric	142	2.03	1/538
Off Center (Type I)	142	3.95	1/277
Off Center (Type II)	142	3.35	1/326
Off Center (Type III)	142	2.79	1/391
Off Center (Type IV)	142	2.75	1/397

Note: Type I specimen had no stiffeners in the cells of the loaded panel, Type II and III had discrete stiffneers in second and fourth cells of the loaded panel, and Type IV had four continuous stiffeners in the cells of the loaded panel.

Table 4. Maximum Deck Deflections in Cellular Panel-Steel Beam System (Sotiropoulus, 1995)

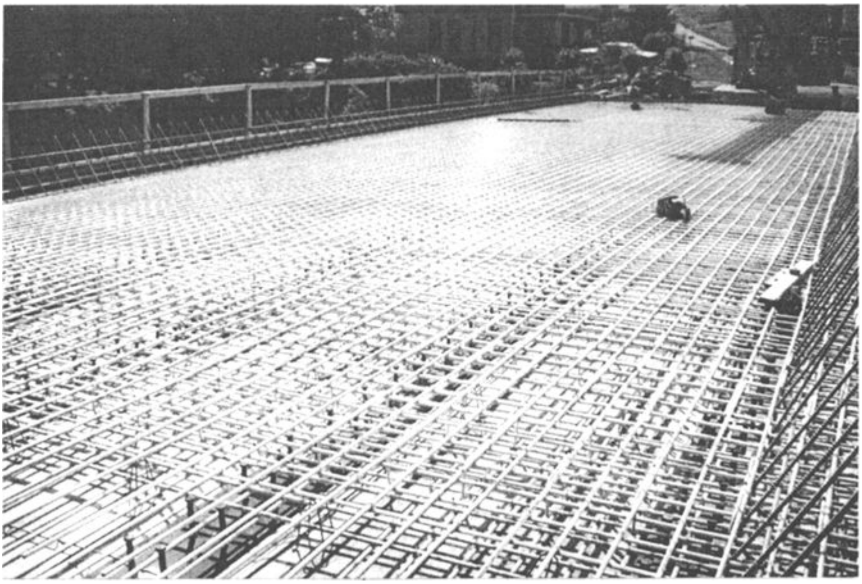

Figure 1. FRP Rebars in Concrete Bridge Deck - McKinleyville Bridge

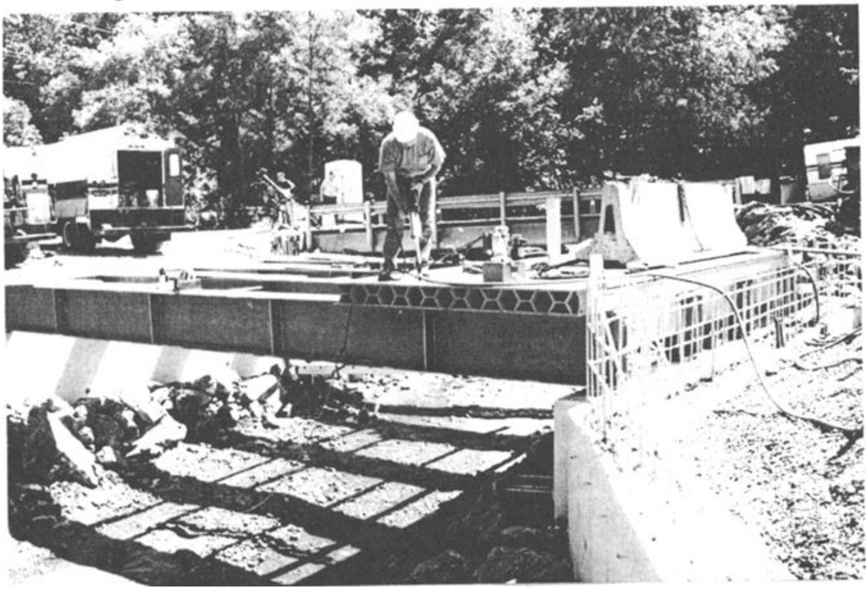

Figure 2. FRP Composite H-Deck (Superdeck^{TM}) - Wickwire Run Bridge