Songklanakarin J. Sci. Technol.
30 (4), 501-508, Jul. - Aug. 2008

Songklanakarin Journal
of Science and Technology

http://www.sjst.psu.ac.th

Original Article

Experimental evaluation and field implementation of FRP bridge deck modules

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Received 2 July 2007; Accepted 24 June 2008

Abstract

Construction of highway bridge decks using fiber reinforced polymer (FRP) composite deck and superstructure modules in lieu of concrete decks has proven to be feasible. However, FRP's are not widely accepted yet despite their benefits such as non-corrosiveness, higher strength to weight ratio, and better fatigue resistance than conventional materials. Lack of wider usage of FRP material is mainly attributed to the absence of: 1) standardized test procedures, 2) design specifications, and 3) construction procedures. The higher initial cost is also inhibiting bridge engineers in selecting FRP modules as highway bridge super structural systems.

Implementation of FRP composites technology for highway bridge decks leads to higher safety and lower life cycle costs. Significant ongoing research and development of FRP deck modules as illustrated herein, has proven to enhance deck module properties in developing FRP modules with enhanced structural performance.

Prodeck 4 is one such multicellular deck that was recently developed, and extensively evaluated for static and fatigue loads, and its response results are presented herein. From rigorous testing, it was concluded that Prodeck 4 could resist AASHTO HS 25 loading with maximum stringer spacing of 48 inches. This led to construction of two bridges (one in Ohio and other in West Virginia) using Prodeck 4 as decking.

Keywords: bridge, fiber, composite, deck, FRP

1. Introduction

Maintenance of modern bridges is exacerbating due to increasing traffic volumes, axle loads and aging. Specifically, bridge deck deterioration due to corrosion is costly leading to accelerated aging and safety hazards. Concrete bridge decks on an average are replaced once in every 20 to 25 years when exposed to deicing chemicals while most other bridge components last for 40 to 50 years or even longer (USDOT-FHWA, 2005). This inherent risk of deck deterioration in highway bridges has highlighted the importance of enhancing their service life. Application of fiber reinforced polymers (FRP) composite materials is proving to be cost-effective and durable either as a new decking system or as a replacement of old decks. For bridge decks with load postings (ratings), FRP decks with lighter self weight (ten times lighter than concrete) enhance bridge deck ratings (O'Connor, 2001). Recent efforts have been proving the effectiveness and advantages in replacing deteriorated concrete bridge decks with advanced FRP composite deck modules.

Composite manufacturers have been developing many FRP composite decks with different cross sections. These decking systems have been developed to overcome certain

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disadvantages of conventional decking materials. In this study, focus is exclusively placed on developing, fabricating, testing, and field implementing one of many different types of FRP decking systems that are in service today. The decking system discussed herein is of multicellular type with the rectangular cross section. This decking system has been evaluated for structural performance by testing the deck in the laboratory, and the decking system was also field implemented.

2. Objective

The main objectives of this study are 1) to experimentally evaluate the FRP deck performance under static and fatigue loads and 2) to provide a summary of field implementation for the Prodeck4 system.

3. FRP Composite bridge deck modules

3.1 General information

The low profile FRP multicellular deck module known as ProDeck4 was designed by researchers at Constructed Facilities Center (CFC), West Virginia University. Prodeck 4 was developed with optimal choice of fiber volume fraction (~50%), fiber orientation (chopped strand mats, triaxial fabrics and rovings) and geometry. Glass fibers were chosen because of their low cost while the choice of the matrix is usually governed by environmental factors. Vinyl ester resins with urethane modifications were suggested to be the best alternative to resist environmental attacks (Vijay and GangaRao, 1999). Prodeck 4 weighs about 11 lbs/ft^2.

The FRP composite components exhibit different thermo-mechanical properties in different directions, unlike steel, which is an isotropic material. The structural properties of the FRP composite deck in different directions discussed herein will be with respect to orientation of the axes, shown in Figure 1.

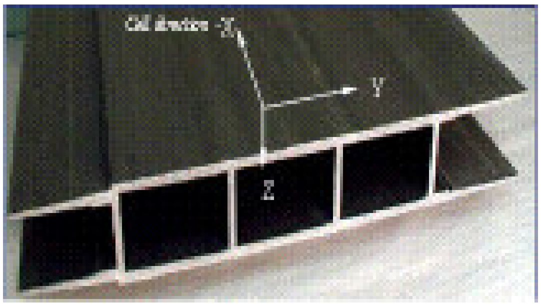


Figure 1. Orientation of Prodeck 4

3.2 Fiber architecture

The FRP bridge decks being studied contained four different types of laminates as: 1) CDBM 3415, 2) DDBM 4015, 3) Roving and 4) Chopped Strand Mat (CSM). It is of interest to note that CDBM 3415 and DDBM 4015 laminates had more than one type of fiber configuration as shown in Tables 1.1 and 1.2. CSM is made of short glass fiber with random orientations. In addition, the dimensions and stacking sequence of ProDeck4 is given in Figure 2. Though FRP composite modules are optimally designed, their structural

Table 1.1 CDBM 3415 Product Specifications

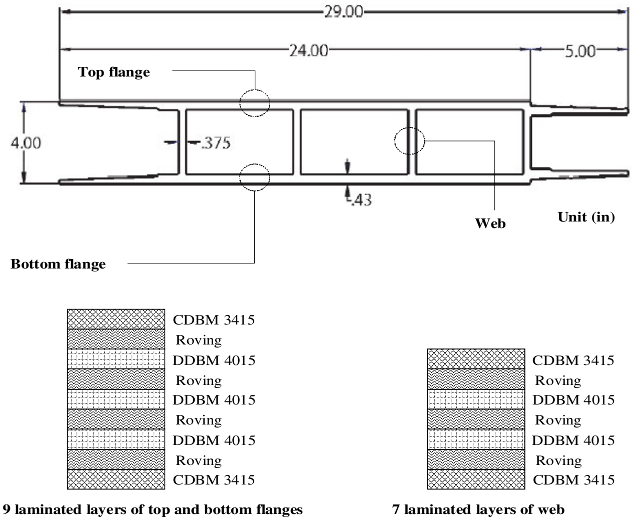
Fiber Type	Nominal Wt. (oz/yd^2)	Thickness (in)	Wf (lb)	Lv(in^3)
0° Fabrics	15.71	0.017	0.1090	2.45
45° Fabrics	9.04	0.0097	0.063	1.397
-45° Fabrics	9.04	0.0097	0.063	1.397
Mat	13.5	0.014	0.094	2.02

Note: Wf = weight of CSM/fabric per square foot (lb),
Lv = volume of 1' x 1' composite laminate (in^3)

Table 1.2 DDBM 4015 Product Specifications

Fiber Type	Nominal Wt. (oz/yd^2)	Thickness (in)	Wf (lb)	Lv(in^3)
45° Fabrics	11.44	0.012	0.0794	1.728
90° Fabrics	17.28	0.019	0.12	2.74
-45° Fabrics	11.44	0.0074	0.0794	1.728
Mat	13.75	0.014	0.094	2.02

Note: Wf = weight of CSM/fabric per square foot (lb),
Lv = volume of 1' x 1' composite laminate (in^3)



9 laminated layers of top and bottom flanges

7 laminated layers of web

Figure 2. Dimensions and Fiber Architecture

performance is affected by fabrication type. Hence in the subsequent section, fabrication of Prodeck 4 modules is discussed in brief.

3.3 Fabricaion

Fabrication of any FRP composite bridge deck modules can be either automated or processed manually. Each process has its own advantages and limitations due to various parameters involved during processing. These parameters are: 1) ease of processing of fibers and resin, 2) efficiency and speed of processing composite constituents into required forms, 3) percent of curing of resins in the presence of fibers and fabrics, and 4) percent of voids.

To achieve optimized mechanical properties, Prodeck 4 was manufactured by a process called pultrusion as shown in Figure 3. The advantages of pultrusion are: 1) low labor cost, 2) low operating cost, 3) minimal material wastage, and 4) high production rate (GangaRao, 1999). Some limitations of the pultrusion process are 1) potential inadequacy of resin wet-out, 2) inadequacy of resin cure, and 3) control of pull speed with minimal voids. Improper resin wet-out and curing will initiate premature failure leading to low mechanical properties of a composite part. With regards to pull speed, it should be kept low to get improved quality of a composite part.

4. Experimental evaluation

The in-service loads might reduce the performance of the FRP decking system in the field. Hence, prior to construction of FRP decking systems on bridges, one needs to fully understand the behavior of an individual component of an FRP bridge deck and their assemblage with other components, such as steel beams. Also connection between FRP deck and steel beam connection needs to be evaluated initially in the laboratory. The following sections provide static and fatigue responses of Prodeck 4 deck stiffened with steel beams through laboratory testing.

4.1 Experimental program

Prodeck 4 modules were tested under both static and fatigue loading. Under static loading, longitudinal and transverse bending tests were performed to evaluate stiffness (both in longitudinal (E_x) and transverse (E_y) modulus) and failure strength of the module. Under fatigue loading, Prodeck 4 modules were subjected to cyclic loading up to 2 million cycles.

4.2 Static performance: longitudinal components

Eight 120" x 24" specimens were tested under bending in the longitudinal (cell or "X") direction. The clear span for the longitudinal FRP bridge deck components was maintained at 108 inch. Three point and four point bending tests were conducted to isolate shear from bending effect of the specimens. Test specimens were subjected to a patch load of 20" x 10" inch. The test set-ups for three-point bending test specimens are shown in Figure 4. Strains and deflections were monitored under static loading to evaluate longitudinal modulus of the component. Longitudinal bending modulus (E_x) was evaluated using both load versus deflection response, and load versus strain response.

Figure 3. Pultrusion Process

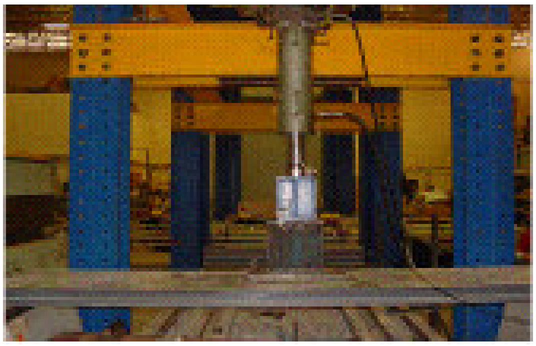
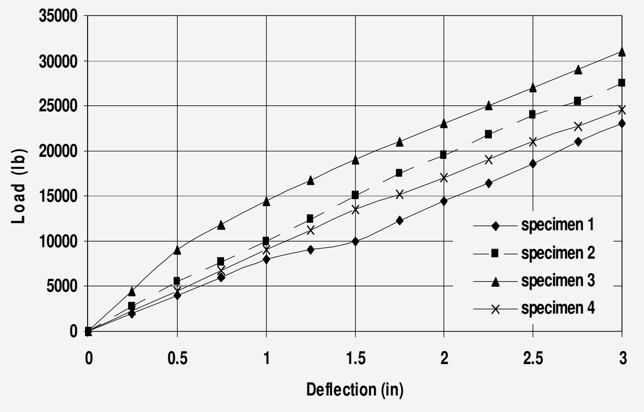
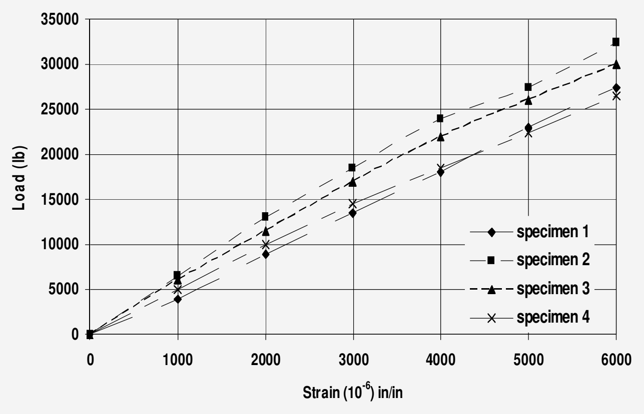


Figure 4. Test Set-up for Three Point Bending Tests



(a) Load versus Deflection Responses



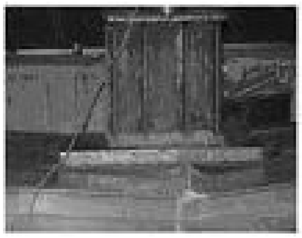
(b) Load versus Strain Responses

Figure 5. Structural Responses under Three Point Bending

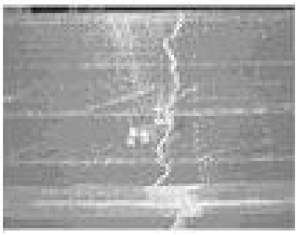
Typical load versus deflection/strain responses are shown in Figure 5, respectively. Three point and four point bending tests revealed that shear deflection is about 10% of the total deflection. On an average (EI_x), of Prodeck 4 is about 2.6 x 10^8 lb-in^2/24 in width, which translates to 0.112 x 10^8 lb-in^2/in width. Since the moment of inertia of one Prodeck 4 module is about 69 in^4, its longitudinal bending modulus (E_x) is about 3.8 x 10^6 psi. Four specimens that were tested to evaluate longitudinal bending modulus of Prodeck 4 were taken to failure under three point bending to evaluate the ultimate bending failure. On an average, the ultimate bending strength of Prodeck 4 is found to be about 32 ksi (Table 2).

The failure modes of specimens were observed through testing of the longitudinal components as follows: In specimens 1, 3 and 4, it is found that the compression flange buckled before the web failure leading to separation of the web and flange under the patch load. For specimen 1, the excessive longitudinal shear stress at the web and flange junction caused the web and flange separation from the failed end to the specimen centerline. The failure mode of specimen 3 is the separation of laminates within the flanges followed by separation at web-flange junction. Specimen 2 also had buckling of compression flange but the failure was initiated with a crack at the bottom flange of the deck (at mid-span) leading to tension failure at the bottom of the deck.

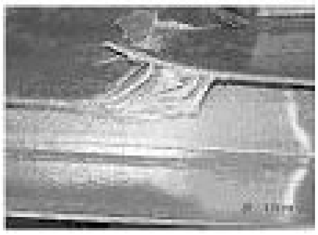
Different types of failure modes during testing are shown in Figure 6. It should be noted that failure modes



a) Web-Flange Separation (specimen 1)



b) Buckling of Top Flange (specimen 2)



c) Delamination in Top Flange (specimen 3)

Figure 6 Failure Modes of Test Specimens

Table 2. Ultimate Strength and Failure Modes

Specimen	Ultimate Load (kips)	Ultimate Strain (10^{-6})	Ultimate Strength (ksi)	Failure Modes
1	35	7577	28	Web/Flange separation leading to compression failure
2	34	5939	NA	Buckling of top flange leading to tension Failure
3	42	9058	35	Compression flange buckling
4	35	8401	32	Compression failure at flange

shown in Figure 6 are very typical in composite modules that are made of multidirectional fabrics (2D fabrics). Using three dimensionally stitched (3D fabrics), i.e., stitching the composite part through its flange or web thickness, will avoid failure modes such as delamination within flanges, web/flange separation etc. in modules which, in turn, will improve the failure strength.

4.3 Static performance: transverse components

Seven 75.6"x 12" specimens with an effective span of 65.6" were tested under bending loads in the transverse (perpendicular to cell) direction. Each specimen consisted of 3 modules, which were connected with polyurethane based adhesive known as PLIOGRIP. The test specimens were reinforced with glass fabric (2 layers of 24 oz) over joints on both top and bottom. Two types of resins, namely epoxy and vinylester, were used to bond fabrics over joints. Four specimens used epoxy to bond fabrics while three other specimens used vinylester.

Three and Four point bending tests were conducted to evaluate transverse bending modulus based on strain data of Prodeck 4. Specimens were placed on rigid supports with steel rollers sandwiched between steel plates to simulate simple support conditions. Strains were monitored during load application. Transverse bending modulus was evaluated using load versus strain response. Test results indicated that there was no significant change in bending modulus between specimens that had fabrics bonded with epoxy and those bonded with vinylester. On an average transverse bending rigidity (EI_y) of Prodeck 4 is about 4.38 x 10^7lb-in^2 /12 in width which translates to 0.36 x 10^7 lb-in^2/in width and average transverse bending modulus (E_y) of Prodeck 4 is about 1.4 x10^6 psi. The bending rigidity for all test specimens is given in Table 3.

It should be noted that the evaluated flexural rigidity based on deflection data is too low, which is attributed to improper transfer of moment from one module to another. From deflection measurement, the location of joints on the component act like a partial hinge, which can partially transfer moment across the joint.

Prodeck 4 was also tested under shear fully to evaluate in-plane and out-of-plane shear modulus, which is not described herein full because it is beyond the scope of this paper. In addition Prodeck 4 was subjected to compressive loads to evaluate ultimate web-buckling strength. The in-plane and out-of-plane shear modulus was approximately found to be about 1/7~1/8th of the longitudinal bending modulus. The ultimate web buckling strength was found to be about 9 ksi/inch width (Prachasaree).

4.4 Fatigue performance: FRP deck-stringer system

Four Prodeck 4 specimens stiffened with steel stringers were tested under fatigue to evaluate their fatigue response as shown in Figure 7. One of the four deck modules was riveted, while others were glued with PLIOGRIP. Three of the four decks were stiffened with two steel stringers (W 10 x 49) system using Z-clips, out of which one was overlayed with Transpo T-48© polymer concrete wearing surface covered with two layers of 6" wide glass fabric and then surfaced with Transpo's Rubbercrete© flexible wearing surface. One of the deck systems was crowned in the center that was stiffened with three steel stringer system (W 10 x

Table 3. Bending Rigidity

Type	Specimen. No	EI (10^8) lb. in^2 (Deflection Data)		3-Point			EI (10^8) lb. in^2 (Strain Data)	
		4-Point	Avg.	Including shear	Excluding Shear	Avg.	4-Point	Avg.
longitudinal	1	-		2.15	2.39		-	
	2	-		2.72	3.0		-	
	3	-		2.44	2.7		-	
	4	-	2.63	2.32	2.58	2.73	-	2.38
	5	2.3		2.23	2.48		2.3	
	6	2.5		2.3	2.56		2.11	
	7	2.97		2.8	3.1		2.72	
	8	2.75		2.72	3.02		NA	
transverse	E-1						0.414	
	E-2						0.492	
	E-3						0.547	
	E-4						0.400	0.438
	VE-1						0.415	
	VE-2						0.437	
	VE-3						0.361	

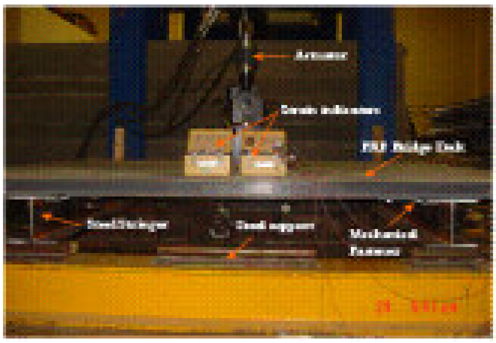


Figure 7. Test Set-up of FRP Bridge Deck System with Two Steel Stringers

Figure 8. Crack at the bottom of the FRP Deck directly beneath the Patch Load

49). The center of the deck was cut parallel to the stringers in order to crown the deck. After the crown was made, a steel plate was attached to the deck to maintain the crown and give continuity to the bottom flanges. This attachment was made using PLIOGRIP and ½ inch diameter bolts. The details of test specimens, stress range, frequency and cycles to failure are given in Table 4.

Specimen number 2 failed prematurely after 495,000 cycles. A visible crack was formed at the deck bottom directly beneath the patch load as shown in Figure 8. The steel plate that was used to simulate a patch load was placed on top of the joint of glued deck system. The plate slipped, due to the uneven surface over the joint caused by excess thickness created by glass fabrics over the joint, thus causing premature failure.

Test specimen number 4 also failed prematurely because failure occurred in the web under the edge of the patch load, as shown in Figure 9. The premature failure is attributed to the fact that one edge of the steel plate was right on top of the web and more load was concentrated on that edge of the plate rather than distributing the load uniformly over the patch. However, our analysis revealed that Prodeck 4 resists AASHTO HS-25 loading over 48" stringer spacing (Punyamurthala, 2004).

Figure 9. Failure Mode for Crowned Deck under Fatigue Loading

5. Field implementation

After rigorous laboratory testing of Prodeck 4 modules, two bridges with Prodeck 4 decking have been successfully installed at two bridge sites, one in Ohio and the other in West Virginia. The superstructure details of the bridges installed in the two sites are given in Table 5.

Before installing Prodeck 4 on the above said bridges, modules were first assembled at the manufacturing site. During fabrication, modules were first made to bridge width

Table 4. Fatigue Testing

No	Deck dimensions (in)	No. of stringers	Stringer spacing(in)	No. of patch loads	Stress Range (*)	Freq. (Hz)	Fatigue cycles	Other details	Remarks
1	120"x101"x4"	2	79"	1	44	1	1,500,000	Panels were riveted	No failure
2	120"x101"x4"	2	79"	1	44	1	495,000	Panels were glued	Premature failure due to shift in the test set-up
3	120"x101"x4"	2	60"	1	36	1	2,000,000	Panels were glued and deck had wearing surface	No failure
4	193"x90"x4"	3	60"	2	36	1	1,000,000	Deck was crowned	Premature failure

Note: Stress range (*) = % of ultimate stress

Table 5. Details of Bridges

Bridge Details	Pleasant Plain Road Bridge - OH	Goat Farm Bridge - WV
Location	Montgomery, OH	Jackson, WV
Length	32 ft.	40 ft.
Width	12 ft.	15 ft.
Depth of Deck	4"	4"
Beam Spacing	8 @ 4 ft. c/c	5 @ 3ft. 6inches
Bridge Railing	Steel	Steel
Wearing Surface	3" bituminous asphalt	3/8" polymer concrete

with 7'-6" to 8'-0" in length. The tongue and groove joint surface was prepared in a carefully laid-out manner before connecting contiguous modules. PLIOGRIP adhesive was then applied to the joint surface of the module, before the adjacent modules were bonded to the first module. The joints in the FRP panels were reinforced with 2 layers of 6" wide glass fabrics of 240 oz/yd^2. Some of those details are shown in Figure 10.

The top flanges of surface of steel stringers were prepared. The FRP composite panels with strong bending axis were then placed transversely to the bridge span (ie. perpendicular to flow of traffic) direction, as shown in Figure 11. FRP deck panels were joined in the field using PLIOGRIP. Once the first panel was placed on the stringers and chemically bonded with PLIOGRIP, the subsequent deck panel was placed next to the first module and the two modules were "squeezed" together to establish good bond and full shear transfer with the remaining panels.

(a) Application of PLIOGRIP

(b) Glass Fabrics over Module Joints

Figure 10 Assembly Process

Figure 11. Deck Placed on Supporting Stringers

Figure 12. Deck-Stringer Connections with Z-Clamps

The FRP decking was connected to stringers by Z clamps as shown in Figure 12. The stringers and FRP deck were predrilled. After the FRP deck was placed on steel stringers, Z clamps were tightened up with bolts. The field joints were reinforced with glass fabrics to prevent cracking of the overlay. Wearing surface of required type and thickness was then laid on the FRP decking system.

6. Conclusions

The various details of FRP composite bridge deck modules are presented herein. From experimental test results, the FRP deck component responses of load versus deflection/strain were found to be linear until failure. The failure modes of the specimens were the compression flange buckling leading to web and flange separation. In addition, Prodeck 4 resists HS 25 loading with maximum stringer spacing of 48 inches.

Superior structural performance of Prodeck 4 led to implementation of Prodeck decking on two bridges i.e, Pleasant Plain Road Bridge at Ohio and Goat Farm Bridge at West Virginia. In order for the FRP decks to become popular, standardized design, testing and construction procedures need to be developed, accepted and implemented by the bridge community. The experience and knowledge gained from the constructions of these two bridges and many other FRP bridges built can be used to develop future FRP bridge deck designs along with testing and construction standards. Also, ongoing monitoring of FRP bridges will validate the long-term performance of FRP decks.

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