Preliminary Design Report

Composite Bridge Decking, Deliverable D3

Publication No. FHWA-HIF-12-021
December 2011

HIGHWAYS FOR LIFE

Accelerating Innovation for the American Driving Experience.

U.S.Department of Transportation
Federal Highway Administration

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HIF-12-021		

4. Title and Subtitle	5. Report Date
Composite Bridge Decking: Preliminary Design Report	December 2011 6. Performing Organization Code
7. Author(s) J. O'Connor	**8. Performing Organization Report No.**
9. Performing Organization Name and Address BridgeComposites, LLC 121 Upper Bennett St. Hornell, NY 14843-1451	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH61-09-RA-00006
12. Sponsoring Agency Name and Address Federal Highway Administration Highways for LIFE Program – HIHL-1 1200 New Jersey Avenue, SE Washington, D.C. 20590	**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**
15. Supplementary Notes	

16. Abstract

This report describes an existing lightweight bridge decking system that is being refined for use on moveable bridges such as bascule spans. The deck is a 5-inch-deep section consisting of fiber-reinforced polymer materials and high-strength grout. Fabrication steps have been simplified, global behavior and local details have been analyzed, and construction details have been developed so that owners can be assured of satisfactory structural performance. Particular attention has been given to the wearing surface, since some other decking systems have not provided long-term durability. While performance has been established as the primary objective, the installed cost must be affordable and competitive against other alternatives when consideration is given to the potential for lower life cycle bridge costs.

The proposed section is symmetrical about a horizontal plane so that it is well suited for the alternating positive and negative bending moments that the deck experiences in service. Deflection controls the design of the deck, and the grout makes an important contribution toward bending stiffness. Alternating the grout between the top and bottom of the deck makes the section stiffer, and presumably more durable, since cracking is less likely to occur due to local deformation. The deck is intended for use on steel stringers spaced up to 5 feet but will first be installed on a town-owned fixed bridge to demonstrate that the installation details have been addressed adequately.

This report documents the early stages of design and constructability discussions so that input can be received from the project's Technical Advisory Panel and other potential stakeholders.

17. Key Words	18. Distribution Statement
Fiber-reinforced polymer, FRP, laminate, bridge decking	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	51	

FORM DOT F 1700.7 (8-72) **REPRODUCTION OF COMPLETED PAGE AUTHORIZED**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

1.0 INTRODUCTION....1

1.1 Project Background....1
1.2 Preliminary Research and Development....2

2.0 PERFORMANCE CRITERIA....5

2.1 Performance Objectives....5
2.2 Design Methodology....6
2.3 Loads....6
2.4 Strength....7
2.5 Serviceability....7
2.6 Weight....7
2.7 Cost....8

3.0 PROPOSED DECK DESIGN....9

3.1 Assumptions....9
3.2 General Description....9
3.3 Geometrics....11
3.4 Materials....14
3.5 Subcomponents....16
3.6 Finite Element Analysis....17
3.7 Fabrication....18
3.8 Quality Assurance....18

4.0 PROOF-OF-CONCEPT INSTALLATION....21

5.0 REFERENCES....27

6.0 BIBLIOGRAPHY....30

7.0 GLOSSARY....33

8.0 ACKNOWLEDGMENTS....35

APPENDIX A: FINITE ELEMENT ANALYSIS....37

APPENDIX B: SIMPLIFIED DESIGN CHECK....41

LIST OF FIGURES

Figure 1. Photo. Typical installation of FRP deck panels on an existing bridge. 1
Figure 2. Photo. Basic configuration of a prototype of the hybrid deck. 3
Figure 3. Diagram. AASHTO HS-20-44 design vehicle. 6
Figure 4. Diagram. Proposed deck on steel stringers. 10
Figure 5. Diagram. Deck cross-section. 10
Figure 6. Diagram. Deck schematic showing components. 11
Figure 7. Diagram. Deck panel. 11
Figure 8. Diagram. Dimensions of inner tube (Part 1) and outer tube (Part 2). 12
Figure 9. Diagram. Part 1 (inner tube). 12
Figure 10. Diagram. Part 2 (outer tube). 13
Figure 11. Diagram. Combination tube (inner and outer tube to be pultruded together). 13
Figure 12. Diagram. Finite element analysis allows the generation of images that graphically illustrate the maximum deflection of the bridge under loading. 17
Figure 13. Diagram. Quality assurance phases. 18
Figure 14. Map. Western New York State with the bridge located with a yellow pin. 21
Figure 15. Map. The Village of Bolivar with the bridge located with a yellow pin. 21
Figure 16. Photos. Existing conditions as of November 2010. 22
Figure 17. Diagram. Existing stringer spacing. 23
Figure 18. Diagram. Existing fascia detail. 23
Figure 19. Diagram. Proposed fascia detail. 24
Figure 20. Diagram. Proposed connection detail. 25
Figure 21. Diagram. Field joint between panels. 26
Figure 22. Diagram. Schematic of proposed wearing surface. 26
Figure 23. Diagram. View of the bridge. 38
Figure 24. Diagram. Magnified view of the deck after applying the loads (around the truck load). 38
Figure 25. Cross-section sketch. 41

LIST OF TABLES

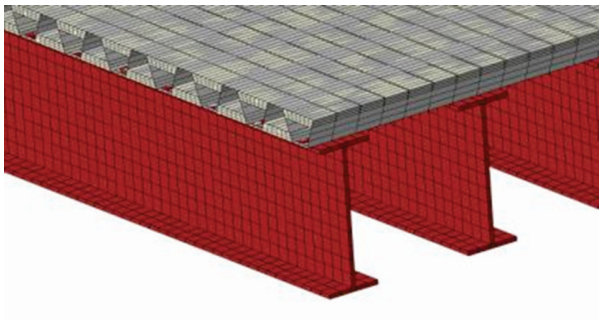
Table 1. Approximate weight of various deck systems. 8
Table 2. Depth of proposed deck section. 11
Table 3. Possible fiber architecture for either tube (inner or outer) 14
Table 4. Possible fiber architecture for the outer wrap. 14
Table 5. Laminate properties. 15
Table 6. Potential sources for tube subcomponents. 17
Table 7. Test procedures. 18
Table 8. FE mesh details. 37
Table 9. Service load deflection and failure index. 37
Table 10. State of stress in the composite. 39
Table 11. Laminate properties. 39
Table 12. State of stress in the concrete. 40
Table 13. Concrete properties. 40
Table 14. Description of parameters. 42
Table 15. Deck beam analysis summary – no factors. 43
Table 16. Deck beam analysis summary – with factors 44
Table 17. Deflection 44

LIST OF ACRONYMS AND ABBREVIATIONS

FHWA	Federal Highway Administration
FRP	Fiber-Reinforced Polymer
HfL	Highways for LIFE
NYSDOT	New York State Department of Transportation
AASHTO	American Association of State Highway and Transportation Officials
LRFD	Load and Resistance Factor Design
FEM	Finite Element Model
NBI	National Bridge Inventory
VARTM	Vacuum-Assisted Resin Transfer Molding
SHM	Structural Health Monitoring
AOTR	Agreement Officer's Technical Representative

EXECUTIVE SUMMARY

Fundamentally, the deck described in this report is the same as the design that was developed and tested by Dr. Amjad Aref between 2003 and 2009 for the New York State Department of Transportation at the University at Buffalo, Department of Civil Structural and Environmental Engineering. Refinements have been made to improve performance while facilitating its fabrication so that the cost per square foot can be reduced. Integral with the design and production improvements are the development of suitable construction details such as connections to the supporting steel and a durable wearing surface.



This illustration depicts a deck on steel beams. It is a hybrid of fiber-reinforced polymer composite materials and grout, made by nesting two trapezoidal tubes to form a 1-inch-thick grout pocket between them. This provides support for truck tires and effectively distributes wheel loads over a wide area. Adjacent tube assemblies are inverted to provide a grouted section on the bottom as well as the top. This provides good bearing strength and a means to connect the deck to the steel firmly. The section, symmetrical about a horizontal plane, will also better handle the alternating positive and negative bending moments that it experiences as a continuous beam over steel supporting stringers. Deflection controls the design of the deck, so the grout is important as a low-cost means of providing bending stiffness, when working in conjunction with the glass fiber-reinforced polymer. Alternating the grout makes the section stiffer, and presumably more durable, since cracking is less likely to occur due to local deformation. The proposed deck is approximately 5 inches thick, after the application of a thin wearing surface. This is a common depth for decks used on moveable bridges.

Further analysis will be required before a final decision is made on the method of fabrication.

After analysis is complete, input is received, and subcomponent testing is done to identify the best combination of materials to use, the deck will be installed on a bridge in Bolivar, NY. The existing Pleasant Street Bridge (BIN 2215390) is 40 feet long by 20 feet wide and will be re-decked using Allegany County forces in May or June of 2012. This process will be similar to the installations envisioned for moveable bridges, which is the primary target of the Highways for LIFE project. A fixed-span bridge was selected to keep the scope small enough that it can be built under the present project.

Input received from the project Technical Advisory Panel is included in this report. Additional comments on this document, as well as all aspects of the design and detailing, are welcome.

1.0 INTRODUCTION

1.1 PROJECT BACKGROUND

The Federal Highway Administration (FHWA) sponsored this project to identify means and methods for the economical production of prefabricated fiber-reinforced polymer (FRP) decking panels for moveable bridges, along with the necessary details for joining and installing them. Over the course of 2 years, studies and testing will be done to identify the most suitable materials, subcomponents, assembly methods, wearing surface, and detailing that will enhance the likelihood of the technology becoming a viable and competitive option in construction practice. Constructability will be demonstrated on a small fixed bridge, with the expectation of using the same design on a large moveable bridge for a subsequent project. Figure 1 illustrates the installation of FRP deck panels on an existing bridge.

Figure 1. Photo. Typical installation of FRP deck panels on an existing bridge.

The FHWA's Highways for LIFE (HfL) program includes a component called Technology Partnerships, which is intended to accelerate the adoption of promising innovations into everyday construction practice by teaming with private industry. The project *Composite Bridge Decking* has been selected because of its potential to yield substantial reward by facilitating the production and deployment of innovative technology that is capable of transforming the construction industry. There are 856 moveable bridges in the U.S., and this type of bridge can reap unique benefits by using a lightweight, yet corrosion-resistant decking system. The project team is tasked with refining the existing equipment, materials, practices, and processes that have been used to produce a hybrid bridge deck comprised of FRP composites and concrete/grout. The project builds on the research and development of a prototype that was done by the New York State Department of Transportation (NYSDOT) at the University at Buffalo over the past 10 years. Since the past research and testing has already shown that the technology is feasible, the purpose of this HfL project is to develop an economical means of producing the hybrid design so that it can be adopted and used routinely for bridge rehabilitations or for new construction.

The HfL project consists of two phases, subdivided into 20 tasks, as shown below.

T1 Project Management

Phase I – Preliminary Design

T2 Define Performance Objectives
T3 Set Deck Geometrics
T4 Create Finite Element Model
T5 Analyze Details
T6 Preliminary Design Review

Phase I – Testing
T7 Qualify Materials
T8 Qualify Tubes
T9 Consider Alternative Assembly Methods
T10 Fabricate & Test 3-Foot by 10-Foot Panels
T11 Evaluate Details
T12 Report
T13 After-Test Review

Phase II - Final Design
T14 Set Final Materials, Tubes & Assembly Methods
T15 Final Design Review
T16 Update Finite Element Model

Phase II – Field Installation
T17 Fabricate Proof-of-Concept Panels
T18 Field Installation
T19 Field Validation
T20 Final Report

As part of the current project, a deck will be fabricated and installed on a small bridge to demonstrate that all details have been addressed adequately. The deck will be installed on a bridge in Bolivar, NY. The existing Pleasant Street Bridge (BIN 2215390) is 40 feet long by 20 feet wide and will be re-decked using Allegany County forces as part of a rehabilitation project in the spring of 2012. This process will be similar to the installations envisioned for moveable bridges, which is the primary target of the HfL project. A fixed-span bridge was selected to keep the scope small enough that it can be built under the present HfL project.

1.2 PRELIMINARY RESEARCH AND DEVELOPMENT

This section of the report describes the deck prototype that was produced at the University at Buffalo prior to the start of the current HfL project (see Figure 2).

Figure 2. Photo. Basic configuration of a prototype of the hybrid deck.

Through the following series of research projects, a deck based on this design was produced and tested:

- Use of New and Durable Advanced Materials for Infrastructure Applications (C008737), 1999-2000.
- Analysis and Design Procedures of FRP Bridge Deck Systems (C008737), 2000-2001.
- Hybrid FRP-Concrete Bridge Deck Systems (C02-07) 2003-2006.

The deck is a hybrid of FRP composite materials and grout, made by nesting two trapezoidal tubes to form a grout pocket between them. The grout near the deck surface provides support for truck tires and effectively distributes wheel loads over a wide area. Since it is much more efficient at carrying compressive loads than FRP materials, it is also an efficient means of increasing strength and stiffness of the section.

2.0 PERFORMANCE CRITERIA

2.1 PERFORMANCE OBJECTIVES

The expectations of the deck system are as follows:

- Excellent technical performance.
    - The deck needs to carry full legal loads repeatedly and must be able to withstand occasional overloads without damage. Global deflection, local deformations, and thermal distortions are to be kept small enough that cracking and spalling do not occur in the wearing surface, internal delaminations do not occur, and fatigue problems do not arise at the connection points. For instance, there was a composite deck that experienced excessive movement around stud shear connectors that were encased in grout pockets. This resulted in deterioration of the connection and loss of intended composite action.
    - Serviceability: Maintenance should be minimal, perhaps limited to cleaning. The wearing surface should stay bonded and not suffer excessive wear. Resurfacing due to polishing should not be necessary for at least 10 years. There needs to be a way to repair the deck if it becomes damaged by impact, puncture, or some extreme event.
    - Service life is expected to exceed that of the bridge on which the deck is placed. For a new bridge, the design life is set at 75 years per the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications.[1]
    - Constructability: The deck should be able to be installed quickly and easily, using light equipment.
    - Adaptability: The system should be able to accommodate future widening or strengthening to accommodate heavier vehicles. With mechanical connections, it also can be removed and reused.
- Lightweight: The weight per square foot should be comparable to other lightweight decking systems.
- Reasonable cost: The primary emphasis will be given to initial material cost per square foot because that is the easiest for owners to understand and measure and is most relevant when budgets are tight. Recognizing that time and ease of installation affect the initial cost, design and detailing will be developed to minimize the installed cost as well as the cost per square foot for material. A long service life with minimal maintenance requirements also will reduce the life cycle cost. Despite these exceedingly important cost considerations, the primary emphasis will be given to initial material cost.

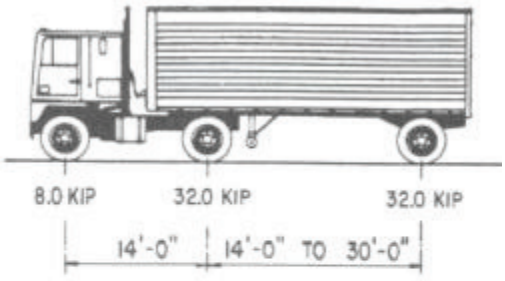
In addition, an effort will be made to develop a deck that is sustainable in the long run. Energy consumption and impact to the atmosphere and water resources should be minimized. Sustainability is becoming an important issue in all fields. According to Daniel, energy consumption of a composite bridge project is less than half that of steel or concrete.[2] It is also attractive when loads to air and loads to water are considered. Future studies may be necessary to calculate the environmental impact of the particular composite deck being considered in the current project.

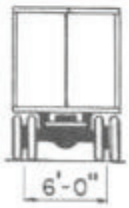
2.2 DESIGN METHODOLOGY

Neither the AASHTO LRFD Bridge Design Specifications nor the AASHTO Standard Specifications for Highway Bridges has explicit provisions for using composite materials in highway bridges.[1,3] As such, the project team is proposing a methodology for FRP (or hybrid decks) that draws from aspects of each specification that has merit and proposes to apply sound engineering judgment to reach a holistic design approach. The Technical Advisory Panel has been involved in the proposed design approach.

2.3 LOADS

Standard AASHTO loading is used in the design of the deck. Figure 3 illustrates the design vehicle used in the Standard Specification for Highway Bridges.[3] The LRFD specification specifies HL-93, which is the HS-20 and lane loading combined. Since the design of the deck is driven by serviceability restrictions (i.e., deflection limits), strength requirements are not anticipated to present a problem, regardless of design vehicle.





Wheel Load		
Per AASHTO LRFD Tire Contact Area Section 3.6.1.2.5		
Contact area = 10-ft length by 20-ft width =	200	sq in
Design Truck		
front axle	8	kips
rear axle 1	32	kips
rear axle 2	32	kips
load on each front wheel	4,000	lb
load on each rear wheel (both tires)	16,000	lb
pressure on each front wheel	20	psi
pressure on each rear wheel	80	psi

Figure 3. Diagram. AASHTO HS-20-44 design vehicle.

2.4 STRENGTH

Analyses have shown that the hybrid deck has excess capacity to carry load because of serviceability considerations (see Appendix A). A finite element analysis and past experimentation show that adding load to the deck system until ultimate failure results in pseudo-ductile behavior prior to failure and that the failure mode is not catastrophic.[4] First failure of a previous prototype was crushing of concrete. However, since composite materials themselves are considered linear elastic to failure, working stresses will be kept low relative to the ultimate strength of the laminate to prevent the possibility of a deck failing without adequate warning. The maximum allowable live load stress will be on the order of 20 percent of ultimate, and dead load will be kept below 10 percent. Though dead load is not significant on a deck, dead load stresses usually are kept low on any composite structure to avoid the potential for creep rupture.

2.5 SERVICEABILITY

As discussed above, the design of the deck is driven by deflection. Criteria for global deflection need to be met (the deflection of the bridge superstructure). Typically, this is set at L/800 (span length divided by 800). In addition, and perhaps more importantly for a deck, local deformation needs to kept low enough that the wearing surface does not crack. The support length between steel stringers is the span that is most important. A three-dimensional analysis will be used to determine the maximum anticipated deflection and the strains at these locations.

2.6 WEIGHT

Since the project involves the development of a deck system specifically for moveable bridges, it is assumed that the weight per square foot is an important consideration. Table 1 provides the relative weight of various decking systems. The objective of the current project is to provide a new alternative to lightweight decking. Although grout is part of the hybrid deck and it adds a significant amount of weight, it is used to help meet the other objectives of good performance and low cost. The grout increases the stiffness of the section and is much more cost-effective than composite material at carrying compressive loads.

Aside from steel used for connecting the deck to the bridge, the proposed deck is projected to weigh approximately 25 psf, excluding a thin wearing surface.

Table 1. Approximate weight of various deck systems.

Deck Type	Weight, excluding wearing surface	Weight, including typical wearing surface
Reinforced concrete (88% of decks, per NBI 12/08)	100-120 psf	100-120 psf
Exodermic	50-75 psf	50-75 psf
Open steel grate	17-55 psf	17-55 psf
Filled steel grate	70 -100 psf	70 -100 psf
Timber	22-30 psf	46-54 psf (assume 2-in asphalt)
FRP	12-25 psf	16-29 psf (assume 3/8-in polymer concrete)
Hybrid (FRP and grout)	~ 25 psf	~28-30 psf (assume ¼-in polymer concrete)
Notes: Use manufacturers' weights for design; the above weights are approximate ranges. NBI = National Bridge Inventory		

2.7 COST

Since a fabrication process has not been established yet, it is too early to project the cost of the proposed deck system. For comparison purposes, it may be worthwhile to point out that the initial unit costs generally are higher than those of conventional concrete decks (~$35/sf). As a rule, 100 percent FRP composite decks have run about three times the cost of a concrete deck. Until production picks up, this deck may be in a similar price range. A deck that has been developed as an alternative for moveable bridges is aluminum decking. The deck developed for NYSDOT is expected to cost less than this option, which is in the range of ~$140/sf.

Although the deck may cost more per square foot, there may be net savings to the project and over the life of the bridge because of its quick installation, low maintenance requirements, and the fact that its service life is expected to be much longer than that of most decks in use today. Savings are also associated with a shorter project because it requires no cure, whereas a concrete deck needs up to 30 days to cure. An FRP deck is prefabricated so it can be driven on almost immediately. A reduction in the duration of a construction project translates to fuel savings, pollution reduction, less wasted time on the part of the driver, and other such benefits.

For moveable bridges, there are additional savings associated with the lightweight nature of the deck. Less mass in the deck means less weight to lift (or move laterally, in the case of a swing bridge) or to account for in the counterbalance. This translates to lower equipment and operational expenses for both mechanical and electrical systems. During bridge rehabilitation, use of a lightweight deck may make it possible to retain the same design dead loads, instead of having to find a way to accommodate a deck system that is heavier than the original. This would result in substantial savings during the rehabilitation project.

3.0 PROPOSED DECK DESIGN

3.1 ASSUMPTIONS

The following assumptions are made in the design of the bridge deck prototype under this project:

- The product will be made in the U.S.
- The prototype deck design is not patent-protected.
- The most important evaluation criteria are performance, weight, and cost.
- Supporting structural members are steel.
- Supporting stringers are typically spaced 5 feet apart or less.
- A mechanical fastening system is preferred over welding. Adhesive bonding may be considered.
- A thin wearing surface is preferred over asphalt because of weight savings.
- Installation procedures should be kept as simple as possible.
- The service life of the deck should exceed that of the bridge it is installed on. This may be an ambitious goal, but the researchers feel that it is very possible with a corrosion-resistant FRP deck. Typically, decks need repair much sooner than the bridge superstructure does, primarily due to rusting of the deck reinforcing steel, but this is not a concern with FRP. The prospect of a long service life is a primary driver for owners' interest in the proposed decking system.
- The deck should be capable of carrying HL-93 service loads without damaging deformation.

3.2 GENERAL DESCRIPTION

The deck section proposed is a hybrid of FRP composite materials and grout, made by nesting two trapezoidal tubes to form a 1-inch-thick grout pocket between them. The cured grout provides support for truck tires and effectively distributes wheel loads over a wide area. Adjacent tube assemblies are inverted to provide a grouted section on the bottom as well as the top. This provides good bearing and a means to connect the deck to the steel firmly. Since the proposed section is symmetrical about a horizontal plane, it will accommodate both positive and negative bending moments equally as well. Finite element analysis and testing of this approach is being done as part of this project.

Although deck panels theoretically are made by making two tubes and grouting between them, an evaluation is underway to determine if better quality is obtainable and the cost of fabrication can be reduced by constructing the tube assembly in one step. The tube assemblies are wrapped in FRP to form a structural panel.

Deck panels can be custom made and oriented on the bridge as necessary. For instance, if a bridge is 20 feet wide and 40 feet long, panels can be have nominal dimensions of 8 feet by 20 feet and placed transversely, as has been done in the past. Alternatively, to facilitate the construction of a crown, the panels may be made lengthwise and shipped to the bridge as 10 feet

by 40 feet. In this case, the structural tubes that are within the panels can still run transversely, perpendicular to the steel stringers.

Figure 4 is an image generated from a finite element model (FEM) that illustrates the proposed cross section. Notice that the grout is alternating between the top and bottom of the deck. This had advantages during the fabrication process because each tube assembly (i.e., the inner and outer tube combined and the cavity between them filled with grout) is identical. The only difference is that every other one is inverted. Figure 5 distinguishes the various components that make up the deck panel: the inner tube, outer tube, the grout between them, and an outer wrap. Figure 6 and Figure 7 show what a panel would look like.

Although it appears that the lack of grout in the top part of some tubes may be a concern, this dimension is only 3.5 inches and will be bridged easily by the footprint of any tire. According to AASHTO, the longitudinal dimension of a truck tire is 10 inches, so the load will be distributed over at least two grouted sections. Local stresses also have been analyzed and do not appear to be a problem. A simplified analysis similar to the one in Appendix B showed that this type of section is over 50 percent stiffer than one with grout only in the top.

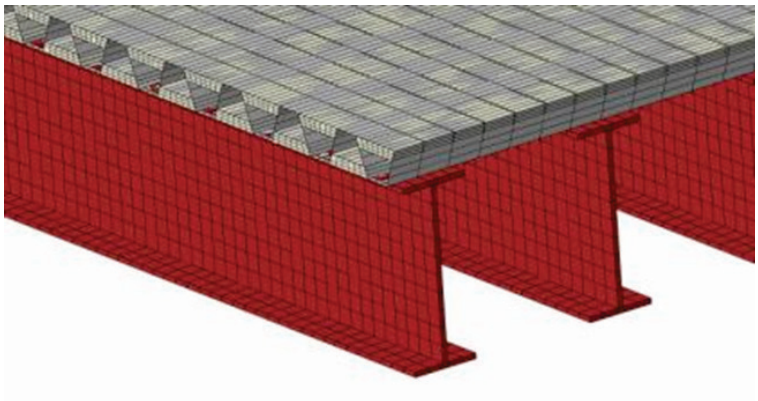


Figure 4. Diagram. Proposed deck on steel stringers.

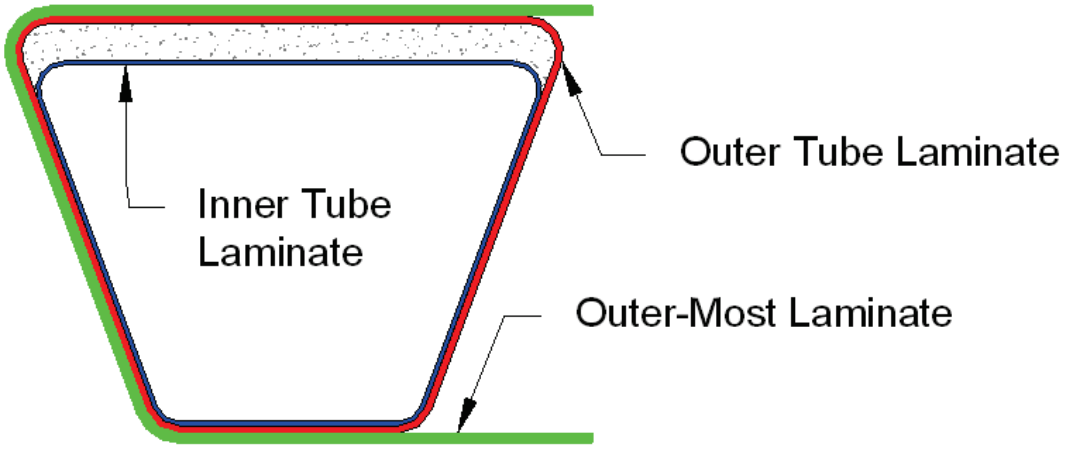


Figure 5. Diagram. Deck cross-section.

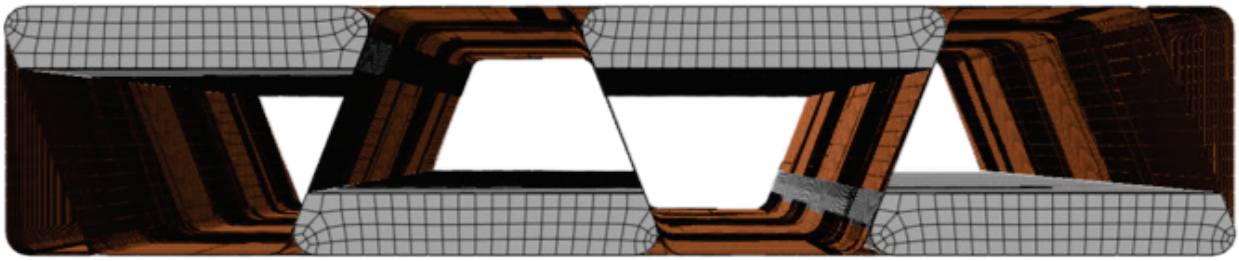


Figure 6. Diagram. Deck schematic showing components.

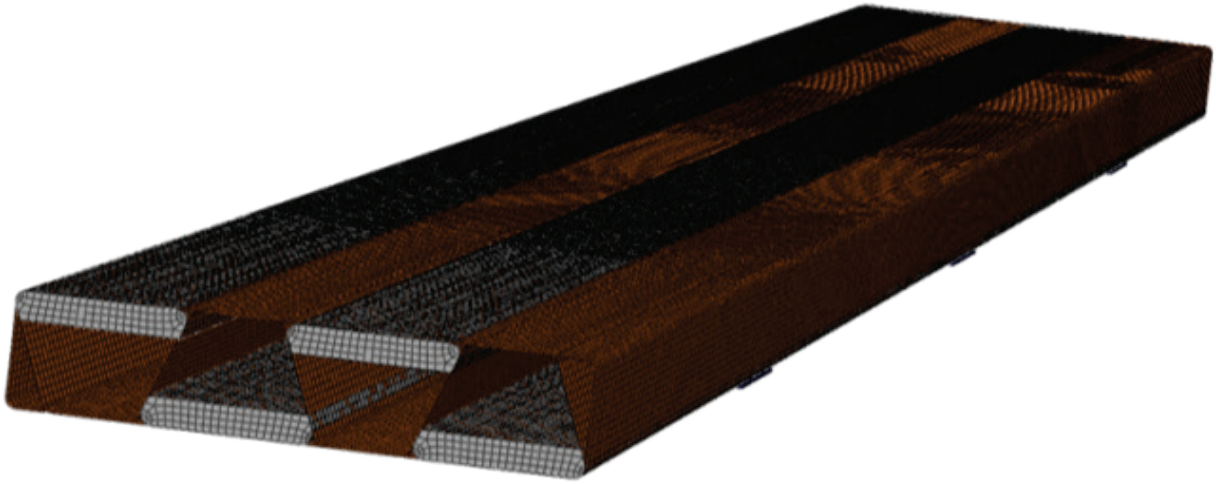


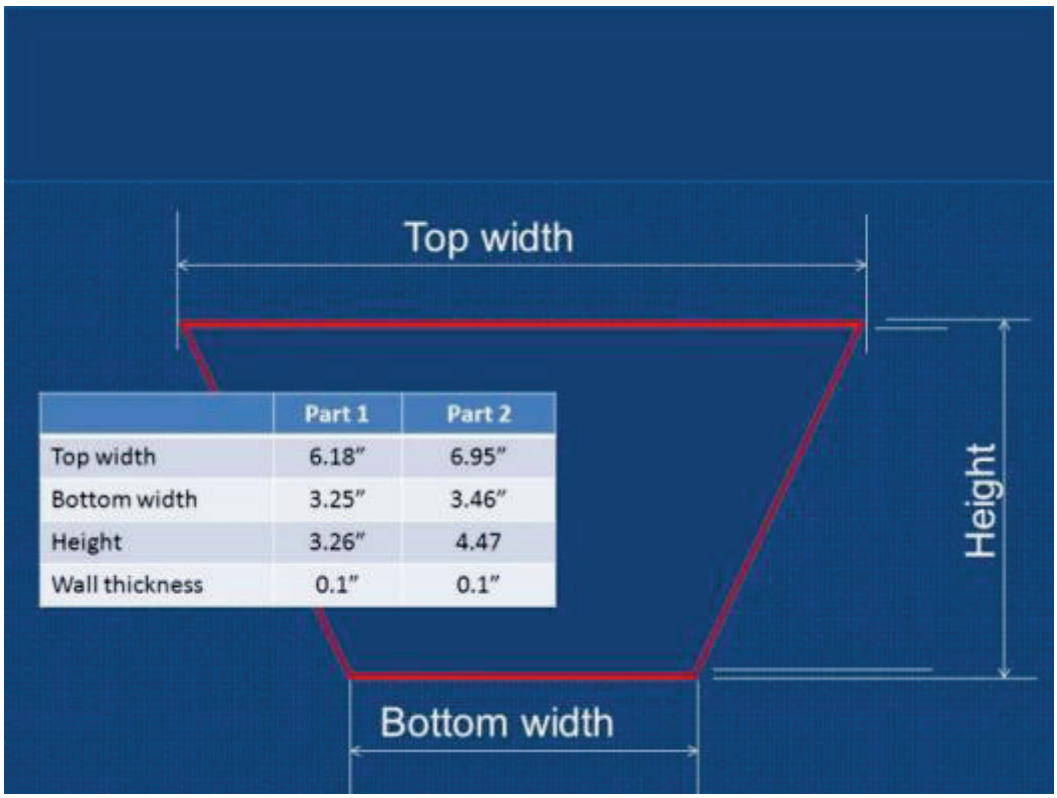
Figure 7. Diagram. Deck panel.

3.3 GEOMETRICS

Whereas Figures 5 through 7 showed the general configuration of the deck, Figures 8 through 11 show the dimensions of the tube subcomponents. The total thickness of the outer wrap is 0.17 inches. The proposed depth of the section can be calculated as in Table 2.

Table 2. Depth of proposed deck section.

Height of outer tube	4.47 in
Thickness of outer wrap on top side of the deck (two layers of VectorPly E-2LTi 7200)	0.17 in
Thickness of outer wrap on bottom side of the deck (two layers of VectorPly E-2LTi 7200)	0.17 in
Subtotal for FRP deck only	4.80 in
Wearing surface (assume polymer concrete)	0.375 in
Total depth including a thin wearing surface	5.175 in



	Part 1	Part 2
Top width	6.18"	6.95"
Bottom width	3.25"	3.46"
Height	3.26"	4.47
Wall thickness	0.1"	0.1"

Figure 8. Diagram. Dimensions of inner tube (Part 1) and outer tube (Part 2).

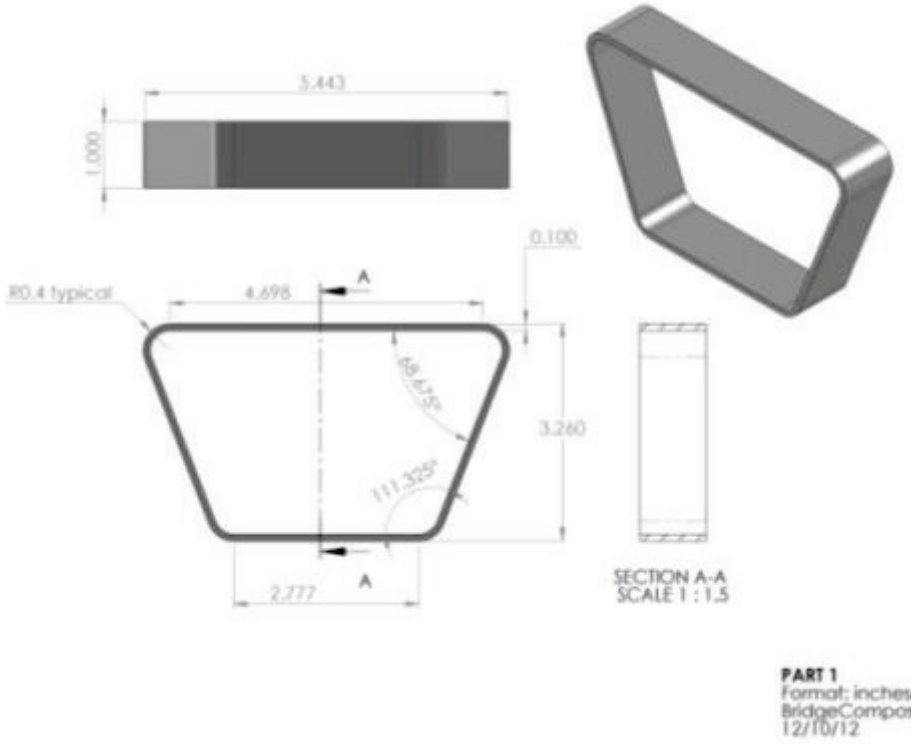


Figure 9. Diagram. Part 1 (inner tube).

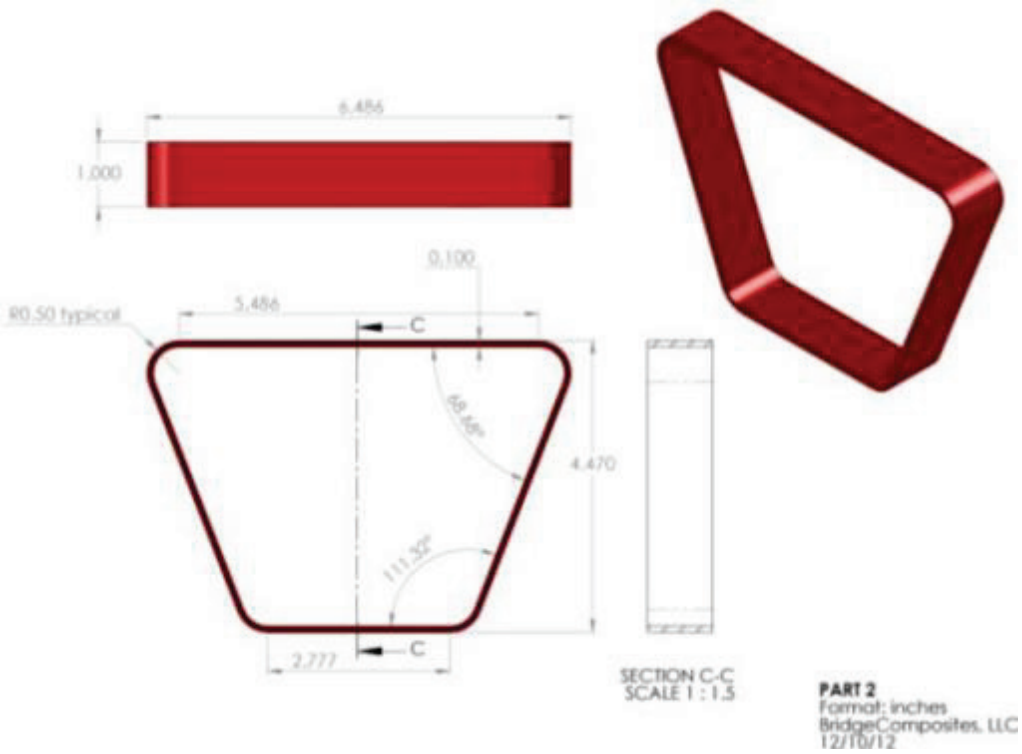


Figure 10. Diagram. Part 2 (outer tube).

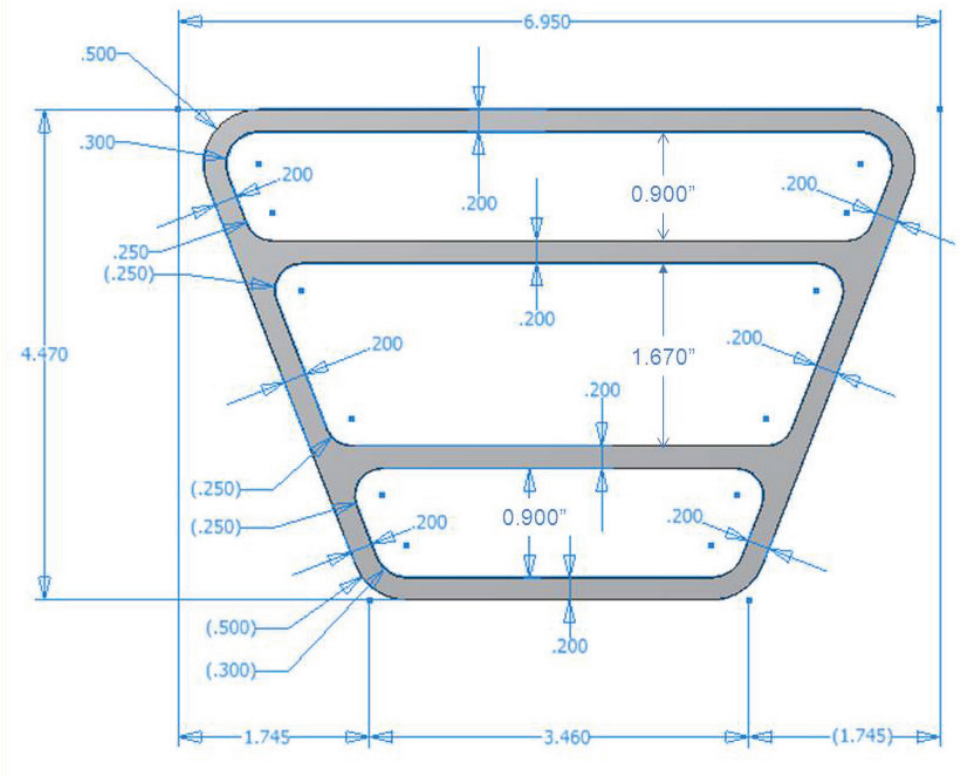


Figure 11. Diagram. Combination tube (inner and outer tube to be pultruded together).

3.4 MATERIALS

3.4.1 FRP Composites

3.4.1.1 Fiber

Table 3 and Table 4 show a combination of E-glass fiber that is being used in trial laminates.

Table 3. Possible fiber architecture for either tube (inner or outer).

Layer #	VectorPly Reinforcement ID	Resin-Infused Laminate Thickness (inches)
1	E-QX 2600	0.026
2	E-LT 5500	0.051
3	E-QX 2600	0.026

Table 4. Possible fiber architecture for the outer wrap.

Layer #	VectorPly Reinforcement ID	Resin-Infused Laminate Thickness (inches)
1	E-2LTi 7200	0.084
2	E-2LTi 7200	0.084

3.4.1.2 Resins

Various resins are being explored. So far, a fire-resistant vinyl ester is the strongest contender.

3.4.1.3 Adhesives

Adhesives are expected to be used in the application of the wearing surface but not in the construction of the deck panel itself. A methacrylate adhesive has very desirable traits. A good bond can be obtained that is strong yet pliable with almost no surface preparation.

The adhesives considered include the following:

- Huntsman Araldite 2048 Methacrylate.
- Dural Fast-Set Epoxy.
- IPS Weld-On SS230 HV Methacrylate.
- ITW Plexus MA-822 Methacrylate.
- 3M Marine-5200-Adhesive-Sealant.
- Ashland Pliogrip 8000 Polyurethane.
- ProSet 176/276 Epoxy.
- Rubber-toughened epoxy.

3.4.1.3 Laminate Properties

Various laminates are being tested. The material used as a benchmark is the laminate that was used in the existing prototype. See Table 5. The properties for the tube and outer wrap given in the table are theoretical values provided by the supplier of the glass reinforcement. The finite element analysis described in Appendix A uses similar property values, but are more refined with each run. The objective is to use values that can be obtained consistently in practice. This will be determined through coupon testing.

Table 5. Laminate properties.

	Reference (Aref/Kitane prototype)	**Tubes (per fiber supplier*)**	**Outer Wrap (per fiber supplier)**
$T_{1\text{-}1\ ult}$ (longitudinal)	48.6 ksi	88.6 ksi	63.0 ksi
$T_{2\text{-}2\ ult}$ (transverse)	41.3 ksi	52.5 ksi	64.0 ksi
$E_{1\text{-}1}$ (longitudinal)	2.60 msi**	4.84 msi	3.35 msi
$E_{2\text{-}2}$ (transverse)	2.41 msi	2.77 msi	3.36 msi
$G_{1\text{-}2}$	0.35 msi	0.71 msi	0.32 msi
V_{ult}	8.1 ksi	13.5 ksi	7.0 ksi
f'_c (longitudinal)	38.4 ksi	60.0 ksi	63.0 ksi
f'_c (transverse)	35.0 ksi	35.8 ksi	64.0 ksi

*VectorPly
** msi = million psi

3.4.2 Grout

Regular strength concrete was used in the early prototypes. Although this material would probably be the least expensive choice, there are other choices that can give better performance. Factors being considered when selecting a grout are:

- Cost.
- Shrinkage.
- Need for cure (time required may hinder the final assembly of the deck).
- Workability (i.e., ease of inserting into the void between tubes or ability to pre-cast).
- Compatibility.

Grouts being considered are listed below:

- Target 1118 non-shrink grout.
- Unitex Propoxy 2000 epoxy grout.
- SolidCast Polyester concrete.
- Sikagrout 212 non-shrink/expanding portland cement.
- Harris construction non-shrink grout.
- Polytops methyl methacrylate grout.
- Chockfast-2821 epoxy grout.

- Lafarge Ductal ultra-high performance concrete.

3.4.3 Wearing Surface

A two-course wearing surface is proposed. There will be one course applied to the panels in the shop. Its primary function is to bond the second course to the deck without debonding or allowing cracking. While polymer concretes used for past applications were intended to do the same thing, there are better adhesives that can provide a strong bond while remaining pliable (i.e., have a high elongation to failure). This pliability would allow it to accommodate differences in thermal characteristics between the deck laminate and the second course of the wearing surface. The second course can be added in the field to provide a highly durable, skid-resistant protective layer. It will bond mechanically to aggregate that is bonded adhesively to the FRP. The second course can be an asphalt material if weight is not a concern. If it is desirable to keep weight low, it can be a thin polymer-modified asphalt or polymer concrete. Alternatives for the wearing surface will be tested in a laboratory over the course of the project to determine the best selection.

3.5 SUBCOMPONENTS

Fabrication of the proposed deck relies upon tube subcomponents that have a trapezoid-like cross section. Efficient production of the deck is based on the premise that these tubes can be commoditized through mass production and competition. The deck panel is an assembly of the tube subcomponents, with grout and an outer wrap added, followed by the addition of a wearing surface.

Fabrication methods being considered for the tubes are hand lay-up, filament-winding, pultrusion, and vacuum-assisted resin transfer molding (VARTM). Each of these has advantages and disadvantages. Hand lay-up has the lowest tooling cost, but the quality (measured by percentage of fiber by volume) may not be consistent. Voids can have a significant negative impact on strength and long-term durability. Pultrusion requires a long-term commitment to a particular shape because tooling and start-up costs are very high. Quality is good because the process is highly automated. VARTM can yield high-quality laminates, and the process retains the flexibility and the ability to change shapes at relatively low cost.

Table 6 lists some potential sources of tubes.

Table 6. Potential sources for tube subcomponents.

Manufacturer	Manufacturing Process	Notes
Plastochem	Hand lay-up	India
Creative Pultrusions	Pultrusion	
CST	Filament or Pultrusion	
Plasan NA	Pultrusion or VARTM	
CompMillenia	Hand lay-up or VARTM	
CompMillenia - Fire	Hand lay-up or VARTM	
XCA	Vacuum infusion	
StructuralComposites	Vacuum with preforms	
Huashi FRP	Pultrusion	China – not responsive
Ancor Plastics	Hand lay-up or VARTM	
Global Composites	VARTM	Use of bottle-core has been determined to be impractical

3.6 FINITE ELEMENT ANALYSIS

Finite element modeling provides a means to investigate stresses and deflections of the deck and structural steel system under various loading conditions. Figure 12 represents the layout of the steel stringers found on the proof-of-concept bridge and illustrates the response on the entire system after a truck load is applied to the deck.

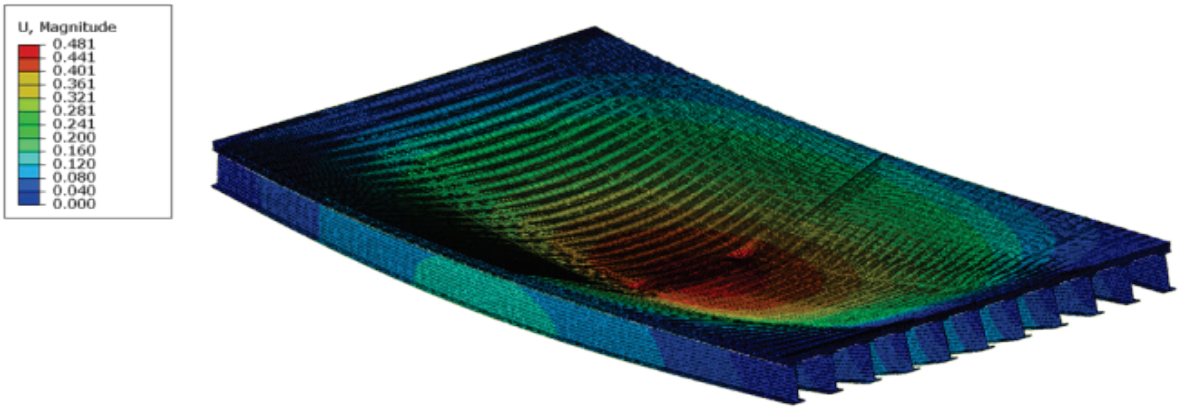


Figure 12. Diagram. Finite element analysis allows the generation of images that graphically illustrate the maximum deflection of the bridge under loading.

3.7 FABRICATION

Fabrication of the deck involves the wrapping of tube assemblies into a panel. A VARTM process is envisioned. This technique is used routinely in boat-building with great success. The fabrication technique being considered is as follows:

1. Fabricate two tubes and pump grout between them.
2. Use inner tube as tooling to create the outer tube and make the tube assembly at the same time.
3. Make one pultrusion that can be used as both the inner and outer tube together.
4. Assemble.
5. Wrap.
6. Apply wearing surface.

Construction details for a field installation are shown in Section 4.

3.8 QUALITY ASSURANCE

Quality will be assessed through visual inspection of manufactured components, a check of the dimensions for compliance with stated manufacturing tolerances, coupon testing of laminates that have been cut out of an actual part, sub-component testing, and full-scale testing of panels. Upon installation of a deck on a bridge, the bridge will be load tested and monitored visually and through non-destructive evaluation (NDE) and structural health monitoring (SHM) techniques. Quality assurance steps are illustrated in Figure 13.

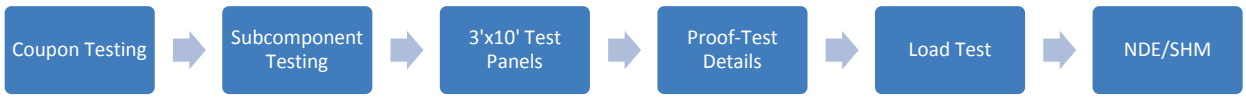


Figure 13. Diagram. Quality assurance phases.

Laminates used for tube construction and the outer wrap will be qualified using the tests listed in Table 7.

Table 7. Test procedures.

Property	Test Protocol
Fiber content by volume	ASTM D3171
Tension	ASTM D3039
Modulus of elasticity (E)	ASTM D3039
Compression	ASTM D6641
Shear	ASTM D5379
Interlaminar shear	ASTM D2344
Shear modulus (G_{xy})	ASTM D2344
Flexure (laminate)	ASTM D790, D2276, D7264
Tube flexure	To be decided
Hardness	ASTM D2583

3.9 Structural Health Monitoring

Numerous health monitoring methods have been investigated. Most have been disqualified because they are cost-prohibitive for all but the most important bridges. At the present time, the team does not plan to embed sensors into the deck at the time of fabrication. Since local deformations are deemed to be the most important parameter to measure, externally mounted sensors can be used to remotely monitor strain levels at critical locations. A wireless system produced by Direct Measurements, Inc. is being evaluated.

4.0 PROOF-OF-CONCEPT INSTALLATION

As part of the current project, a deck will be fabricated and installed on a small bridge to demonstrate that all details have been addressed adequately. The deck will be installed on a bridge in Bolivar, NY. The existing Pleasant Street Bridge (BIN 2215390) is 40 feet long by 20 feet wide and will be re-decked using Allegany County forces in 2012. The following figures show the location and proposed details.

Figure 14. Map. Western New York State with the bridge located with a yellow pin.

Figure 15. Map. The Village of Bolivar with the bridge located with a yellow pin.

Figure 16. Photos. Existing conditions as of November 2010.

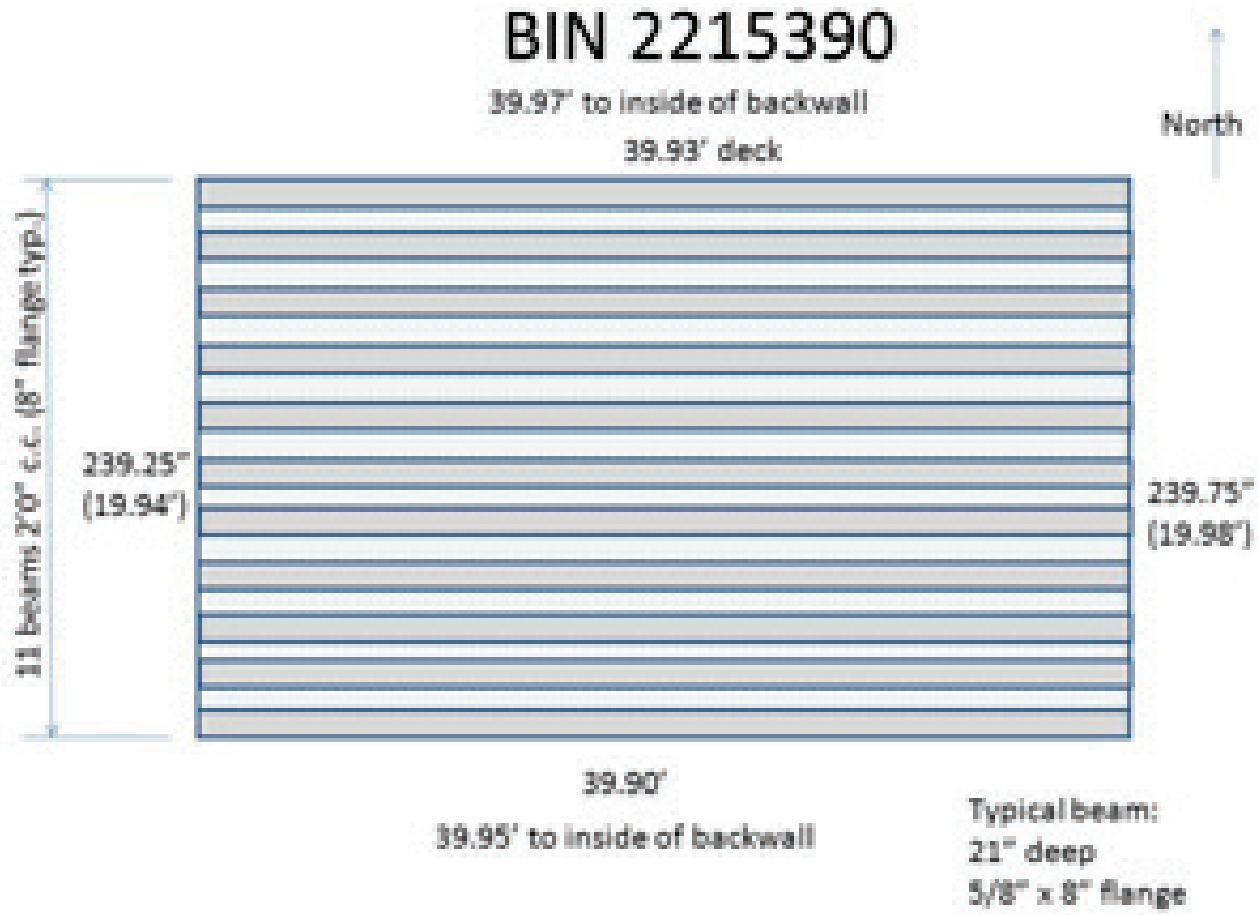


Figure 17. Diagram. Existing stringer spacing.

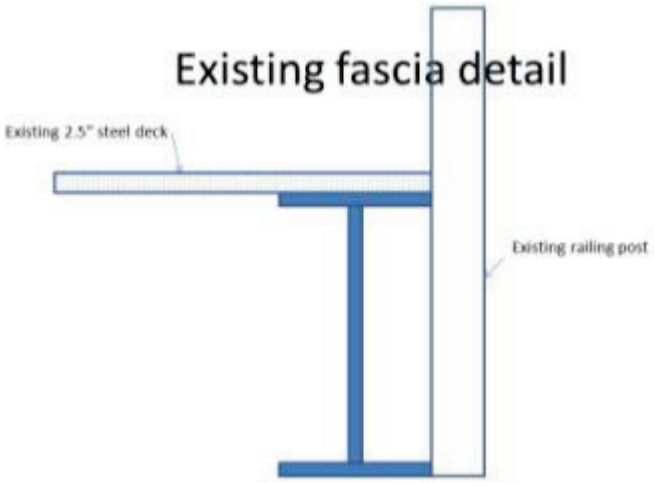


Figure 18. Diagram. Existing fascia detail.

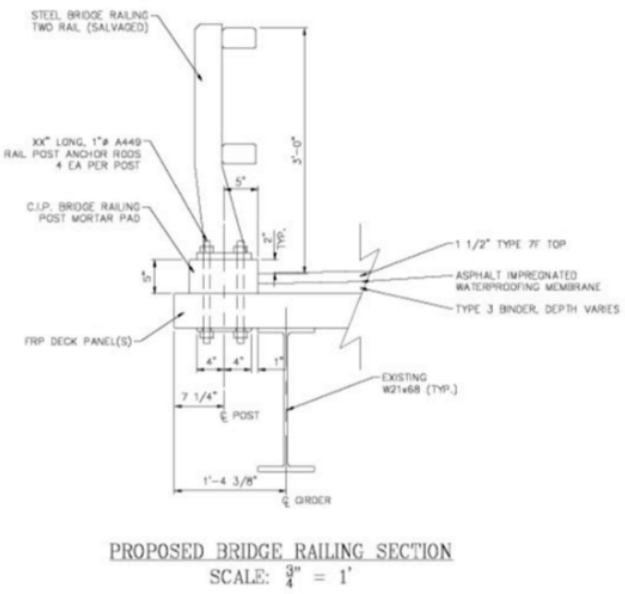


Figure 19. Diagram. Proposed fascia detail.

The anchorage detail will be analyzed per the AASHTO LRFD specification and proof-tested as part of the project. The bridge is an off-system bridge, so the County plans to reuse bridge railing that was previously on a NYSDOT bridge.

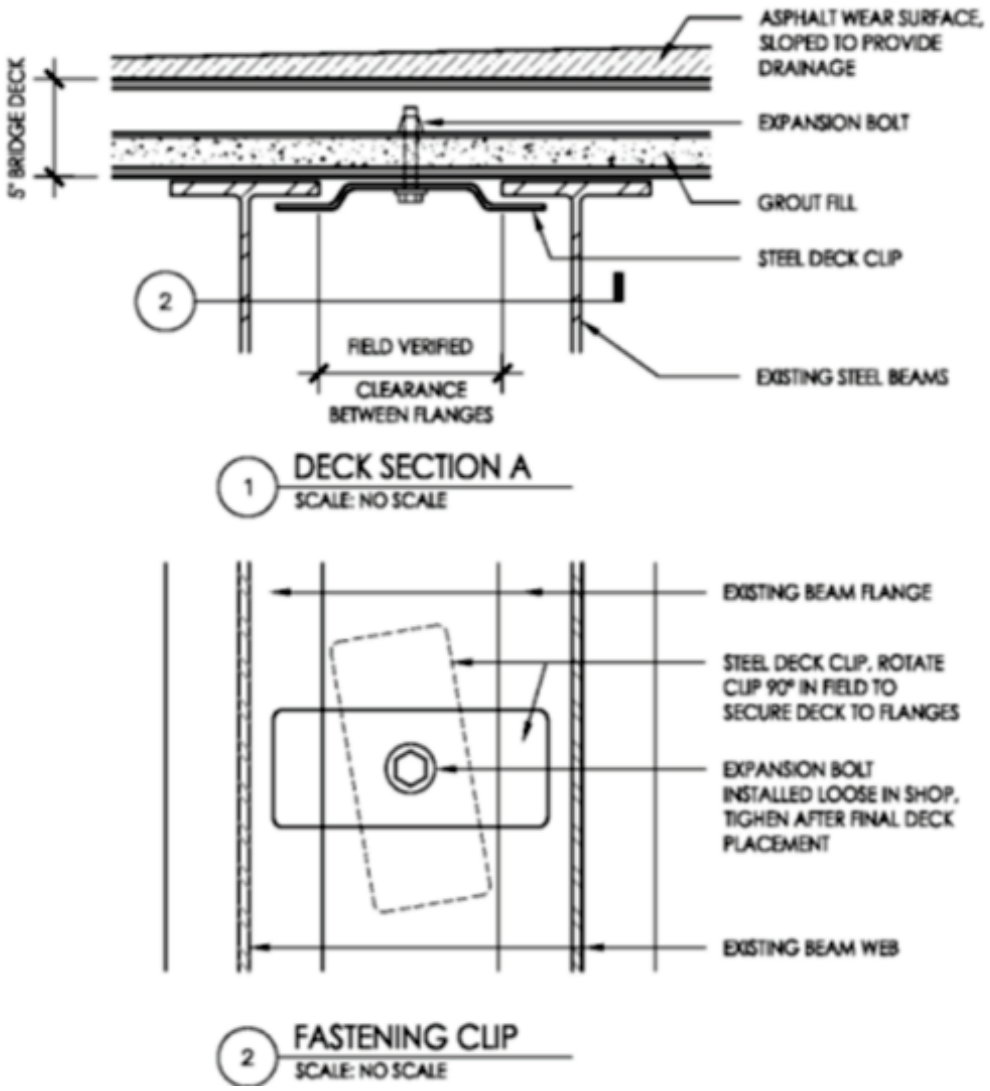


Figure 20. Diagram. Proposed connection detail.

Spacing to be determined during final design.

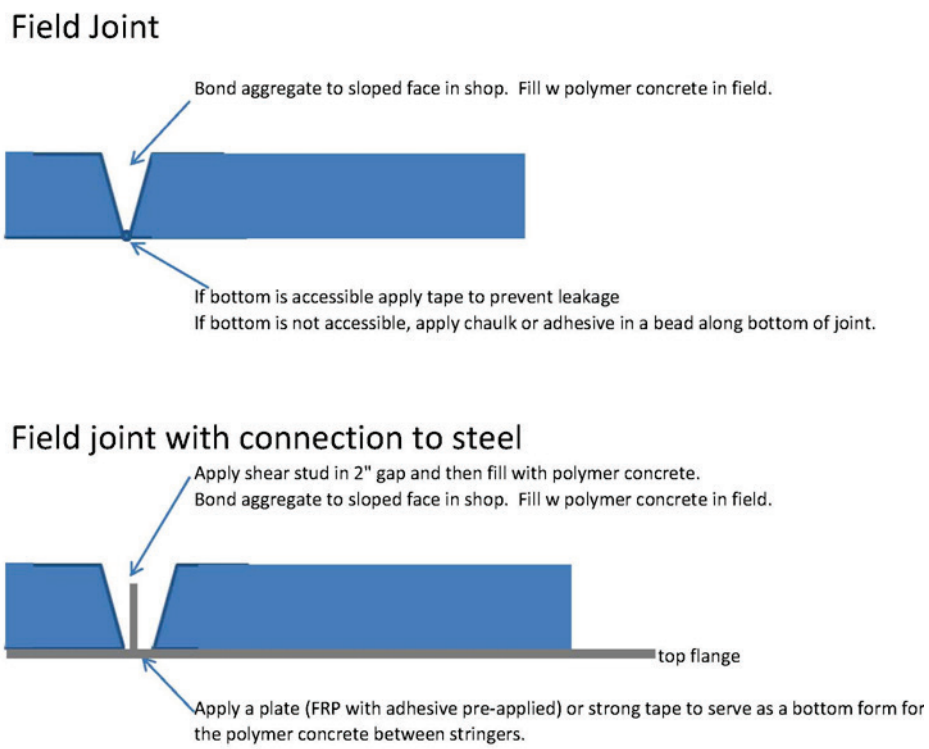


Figure 21. Diagram. Field joint between panels.

The stud will be used to provide resistance to longitudinal forces such as braking forces.

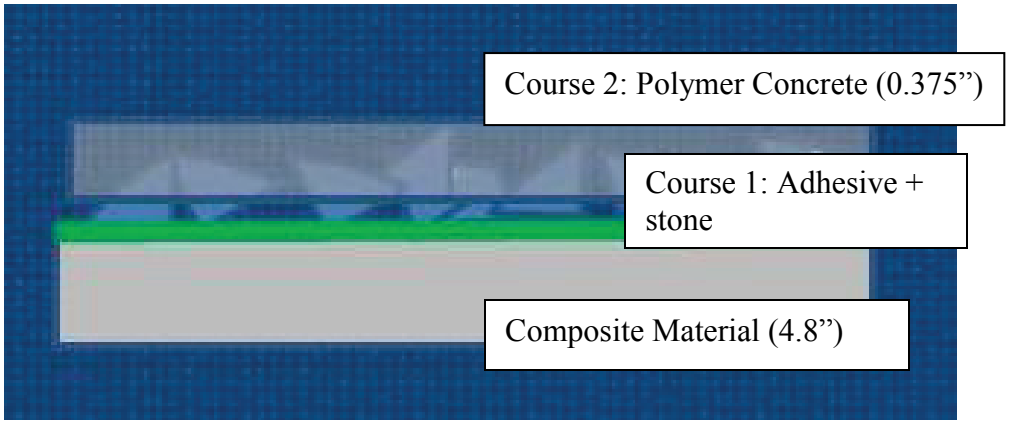


Figure 22. Diagram. Schematic of proposed wearing surface.

5.0 REFERENCES

1. American Association of State Highway and Transportation Officials, *LRFD Bridge Design Specifications*, 3rd ed., AASHTO, Washington, DC, 2010.

2. Daniel, R.A., "A Composite Bridge is Favoured by Quantifying Ecological Impact," *Structural Engineering International*, vol. 20, no. 4, 2010, pp. 385-391.

3. American Association of State Highway and Transportation Officials, *Standard Specifications for Highway Bridges*, 17th ed, AASHTO, Washington, DC, 2002.

4. Aref, A.J., and W.I. Alnahhal, *Hybrid FRP-Concrete Bridge Deck Systems*, Report No. C-02-07, New York State Department of Transportation, Albany, 2009.

6.0 BIBLIOGRAPHY

Aboutaha, R.S., "Investigation of Durability of Wearing Surfaces for FRP Bridge Decks," Project C-01-50, Syracuse University and Cornell University, 2001, 397 pp.

Alampalli, S., J. O'Connor, and A.P. Yannotti, "Advanced Composites for Cost-Effective Rehabilitation of Bridges," in *Advances in Composite Materials and Mechanics*, A. Maji, ed., ASCE, Reston, VA, 1999, pp. 76-84.

Alnahhal, W.I, M. Chiewanichakorn, M., A.J. Aref, and S. Alampalli, "Temporal Thermal Behavior and Damage Simulations of FRP Deck," *Journal of Bridge Engineering*, vol. 11, no. 4, 2006, pp. 452-465.

Aref, A.J., and S. Alampalli, "Vibration Characteristics of a Fiber-Reinforced Polymer Bridge Superstructure," *Composite Structures*, vol. 52, no. 3-4, 2001, pp. 467-474.

Aref, A.J., S. Alampalli, and H. Yihong, "Performance of a Fiber-Reinforced Polymer Web Core Skew Bridge Superstructure, Part I: Field Testing and Finite Element Simulations," *Composite Structures*, vol. 69, no. 4, 2005, pp. 491-499.

Aref, A.J., S. Alampalli, and H. Yihong, "Performance of a Fiber-Reinforced Polymer Web Core Skew Bridge Superstructure, Part II: Failure Modes and Parametric Study," *Composite Structures*, vol. 69, no. 4, 2005, pp. 500-509, (2005).

Aref, A.J., Y. Kitane, and G. Lee, "Analysis of Hybrid FRP-Concrete Multi-Cell Bridge Superstructure," *Composite Structures*, vol. 69, no. 3, 2005, pp. 346-359.

Better Roads, Bridge Inventory issue, November 2010.

Chiewanichakorn, M., A.J. Aref, and S. Alampalli, "Failure Analysis of a Fiber-Reinforced Polymer Bridge Deck System," *Journal of Composites Technology and Research*, vol. 25, no. 2, 2003, pp. 119-128.

He, Y. and A.J. Aref, "A Semi-Analytical Procedure for Simplified Design of Bidirectional FRP Web-Core Sandwich Bridge Decks," *International Journal of Computational Engineering Science*, vol. 3, no. 2, 2002, pp. 129-154.

He, Y. and A.J. Aref, "An Optimization Design Procedure for Fiber Reinforced Web-Core Sandwich Bridge Deck Systems," *Composite Structures*, vol. 60, no. 2, 2003, pp. 183-195.

Kitane, Y., A.J. Aref, and G. Lee, "Static and Fatigue Testing of Hybrid Fiber-Reinforced Polymer–Concrete Bridge Superstructure," *Journal of Composites for Construction*, vol. 8, no. 2, 2004, pp. 182-190.

O'Connor, J.S., "Rapid Replacement of a Short Span Bridge Using a Pre-Fabricated Lightweight Superstructure," *Proceedings of the Fourth US-Taiwan Bridge Engineering Workshop,* Princeton, NJ, 2008.

O'Connor, J.S., and A. Aref, "New Materials in Infrastructures: The FRP Experience," *Aging Infrastructures Workshop Proceedings,* U.S. Department of Homeland Security, pp. 131-135, 2009.

O'Connor, J.S., A. Aref, and S. Alampalli, "Strategic Development and Deployment of a Composite Bridge Deck," *Advanced Composites in Construction (ACIC) 2011 Conference Proceedings*, University of Warwick, UK, 2011.

O'Connor, J.S., and J.M. Hooks, "Experience in the United States with Fiber-Reinforced Polymer Composite Bridge Decks and Superstructures," *6th International Bridge Engineering Conference: Reliability, Security, and Sustainability in Bridge Engineering*, Transportation Research Board, 2005, pp. 57-66.

O'Connor, J.S., and J.M. Hooks, "A Summary of Six Years Experience Using FRP Composites for Bridge Decks," *Society for the Advancement of Material & Process Engineering (SAMPE) Conference Proceedings*, Long Beach, CA, 2004.

O'Connor, J.S., and J.M. Hooks, "USA's Experience Using Fiber Reinforced Polymer (FRP) Composite Bridge Decks to Extend Bridge Service Life," *Proceedings of the 19th US-Japan Bridge Engineering Workshop*, 2003, pp. 237-248.

Triandafilou, L.N., and J.S. O'Connor, "Field Issues Associated with the Use of FRP Composite Bridge Decks and Superstructures in Harsh Environments," *Structural Engineering International*, vol. 20, no. 4, 2010.

7.0 GLOSSARY

Composite Behavior
Two structural components acting in unison as one.

Composite
Any material with more than one constituent that assumes properties that are different from the constituents. FRP is an example; these materials are referred to as FRP composites.

Hybrid
A structural component comprised of more than one material, such as FRP and grout.

Part 1
Inner trapezoidal tube.

Part 2
Outer trapezoidal tube.

Tube Assembly
The assembled combination of one inner and one outer tube with grout between them.

Tube
An FRP subcomponent of the deck panel with a cross-section that is roughly trapezoidal.

Wearing Surface, Course 1
Aggregate adhesively bonded to the FRP panel, whose primary purpose is to provide 100 percent bond while remaining pliable enough to withstand extreme deflection and temperature swings.

Wearing Surface, Course 2
A thin polymer concrete layer applied to course 1 of the wearing surface, whose primary purpose is to provide a highly durable, skid-resistant, protective coating for the deck. An asphalt layer can be used in lieu of polymer concrete when weight is not an issue.

Wrap, or Outer Wrap
The FRP laminate that encases a series of tube assemblies to form a deck panel.

8.0 ACKNOWLEDGMENTS

FHWA's Agreement Officer's Technical Representatives (AOTR's) are Julie Zirlin and Lou Triandafilou.

Others' roles are as follows:

Technical Advisors:
- Steve Winckler, Global Composites.
- Laurence Gray, G5 Technologies (industrial manufacturing experience).
- John Young, Consultant (Six-Sigma black belt).
- Ed Stewart, Consultant (wind turbine experience).

Technical Advisory Panel:
- Ray Bottenberg, OR DOT.
- Duane Daniels, Larson Design Group.
- Jeremy Ferris, Allegany County.
- Paul Fossier, LA DOTD.
- Paul Liles, GA DOT.
- William Potter, FL DOT.
- Herbert Protin, HDR.
- Tom Sheehan, NYSTA Canals Division.
- Kevin Thompson, Arora & Associates, PC.
- Art Yannotti, NY DOT.

Project Management Advisory Panel:
- Sreenivas Alampalli, NYSDOT.
- Paul McAnany, PE.

Project Team:
- Amjad Aref, Integrated Materials and Applied Computing, Inc.
- Stephen Ayers, LeTourneau University.
- Maria Lopez de Murphy, Penn State University.
- BridgeComposites, LLC (Jerome O'Connor, Kate O'Connor).
- XC Associates, Inc. (Frank Burzesi, Lynda Fiorini, Dave Loucks).

APPENDIX A: FINITE ELEMENT ANALYSIS

Composite Bridge Decking
Grant Number DTFH61-09-RA-00006
Highways for LIFE Technology Partnerships Program

FE Analysis of FRP Deck, by Amjad J. Aref

April 12, 2011

FINITE ELEMENT MODEL

This short summary reports the finite element results of the preliminary design of the FRP deck on steel girders.

Table 8. FE mesh details.

Part	Element Type	Elements	Nodes
FRP	S4R	147374	137844
Concrete	C3D8R	119700	185440
Steel	C3D8R	22880	49588
Total		289954	372872

RESULTS

Using AASHTO LRFD Bridge Design Specifications:

Load Factor for Lane Load = 1.75
Load Factor for Truck Load = 1.75*(1+0.33)= 2.3275

Table 9. Service load deflection and failure index.

Loading	Maximum deflection (in) (Service Load)	Tsai-Hill Index (I_{TH}) (LRFD)
HL-93	0.373	0.443

Note: The deflection is measured under the service load.

Maximum Local Deflection between 2 girders = 0.035 in

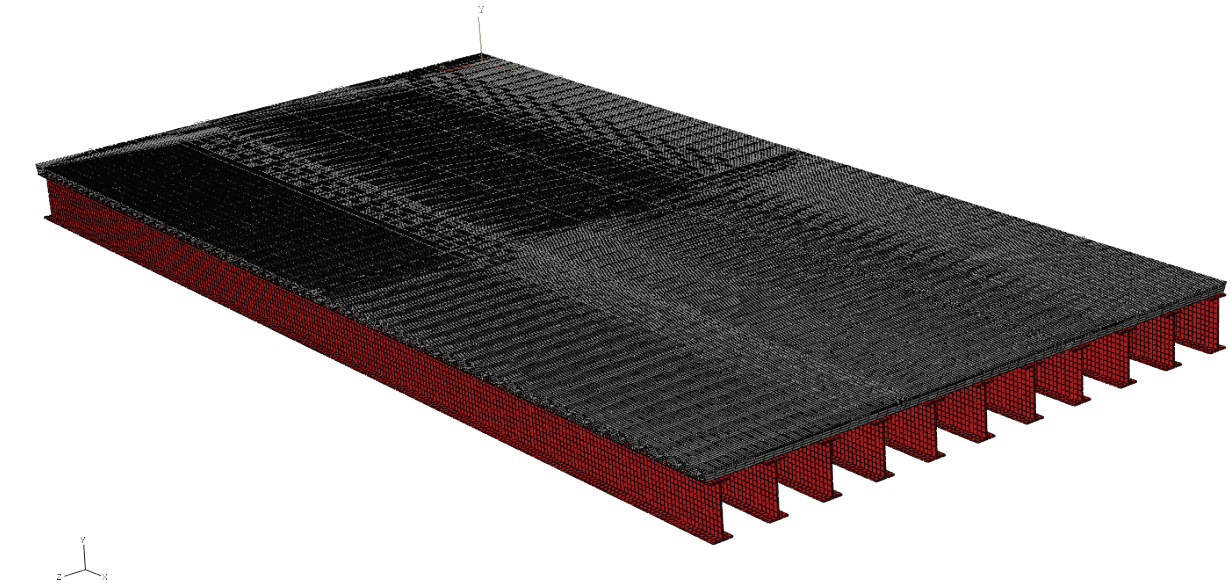


Figure 23. Diagram. View of the bridge.

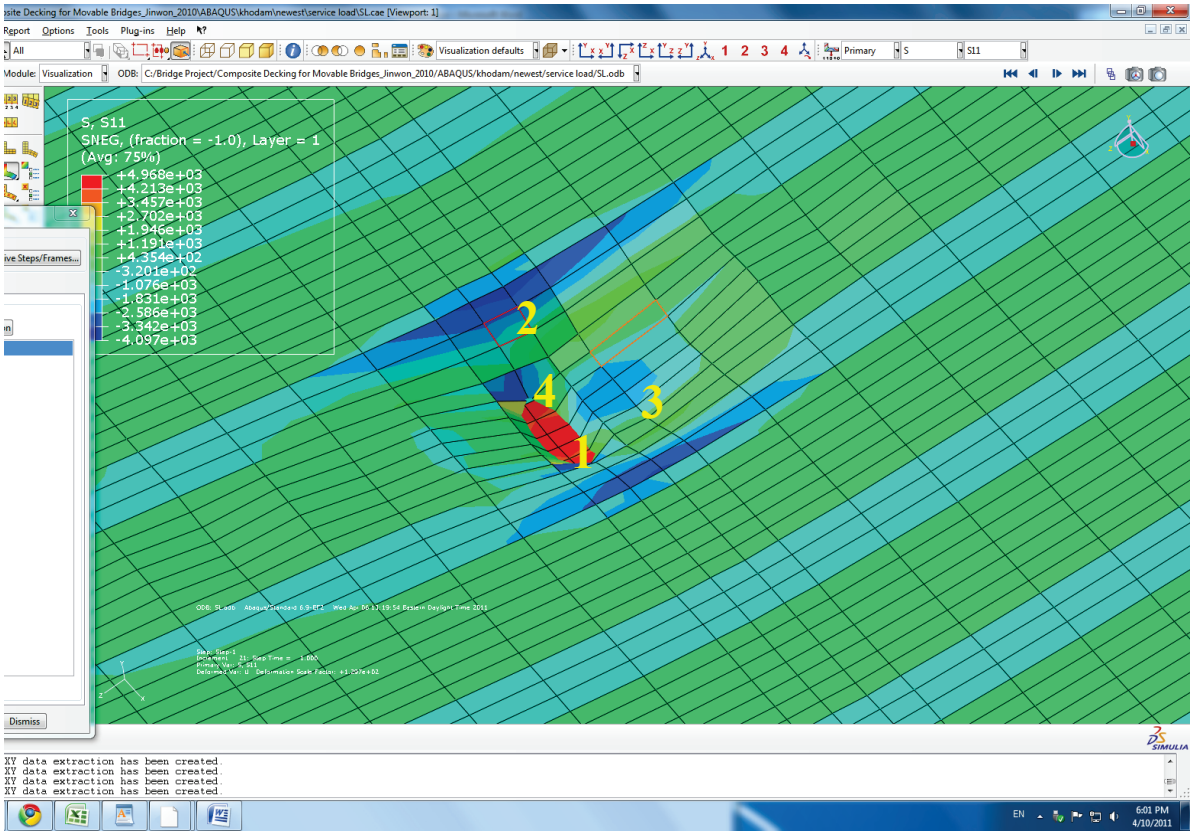


Figure 24. Diagram. Magnified view of the deck after applying the loads (around the truck load).

Table 10. State of stress in the composite.

Element No.	S_{11} (psi)	% of ultimate	S_{22} (psi)	% of ultimate	S_{12} (psi)	% of ultimate
1	5500	6.2	2500	4.8	0	-
2	-4000	6.6	-1300	3.6	250	1.8
3	-2000	3.3	-7200	20	30	0.2
4	-2000	3.3	-2500	6.9	1500	11.11

Table 11. Laminate properties.

Laminate	Unit	Value
Elastic modulus of 0 degree, Ex	psi	4.84E+6
Elastic modulus of 90 degree, Ey	psi	2.77E+6
Shear modulus, Gxy	psi	0.71 E+6
Ultimate tensile strength of 0 degree	psi	88.6 E+3
Ultimate tensile strength of 90 degree	psi	52.5 E+3
Ultimate compressive strength of 0 degree	psi	60.0 E+3
Ultimate compressive strength of 90 degree	psi	35.8 E+3
Ultimate shear strength	psi	13.5 E+3
Possion's ratio		0.3

Table 12. State of stress in the concrete.

Element	S_{11} (psi)	% of ultimate	S_{22} (psi)	% of ultimate	S_{12} (psi)		S_{33} (psi)	% of ultimate
top	-1200	9	-450	3.4	-250	-	-1200	9.1
bottom	1250	53.2	75	3.2	-120	-	1000	42.5

Table 13. Concrete properties.

Properties	Unit	Value
Compressive strength	psi	1.32E+4
Tensile strength	psi	2.35E+3
Elastic modulus	psi	2.16E+6
Possion's ratio		0.2

APPENDIX B: SIMPLIFIED DESIGN CHECK

Composite Bridge Decking
Grant Number DTFH61-09-RA-00006
Highways for LIFE Technology Partnerships Program

Beam analysis of alternating grout, by Steven Winckler, Global Composites.

May 2, 2011

DECK BEAM ANALYSIS

This analysis refers to the document "PM2 BC Basic design formulas-Alternating Grout.docx" for the formulas used.

The loading considered is an ASHTO tire, 20" wide by 10" @ 80 psi pressure.

The deck is modeled as a beam 9.5" wide (one representative element), a span of 24" (girder spacing), and includes 2 webs.

Typical "Alternating Grout" Deck Section

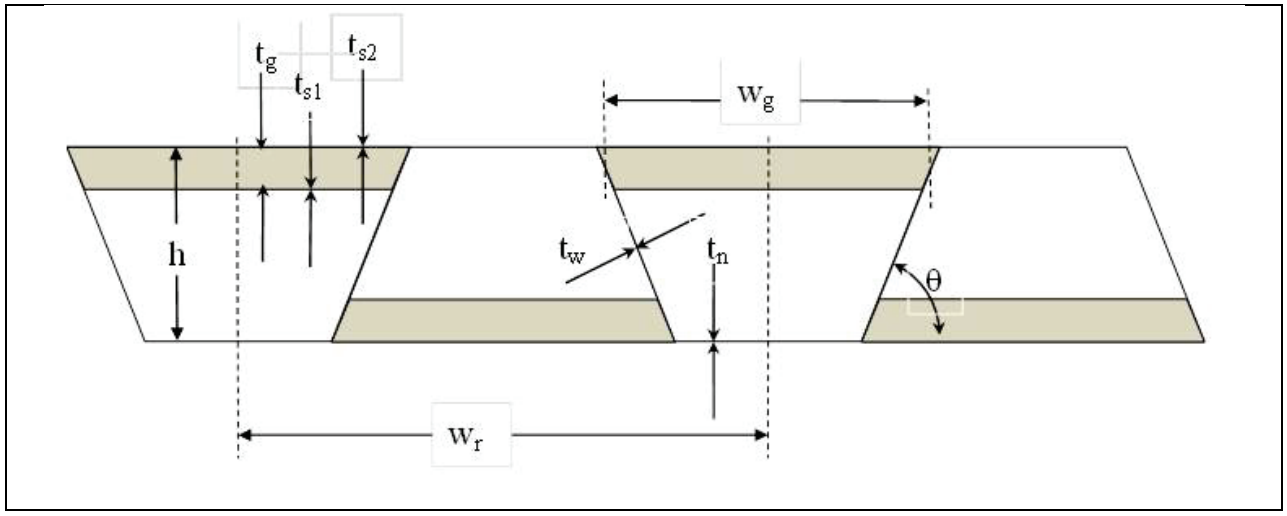


Figure 25. Cross-section sketch.

Table 14. Description of parameters.

Parameter	Description
h	Total deck height
w_g	Average width of grout section
w_r	Width of representative element
t_g	Thickness of grout
t_{s1}	Thickness of inner grout skin laminate
t_{s2}	Thickness of outer grout skin laminate
t_w	Thickness of web laminate
t_n	Thickness of narrow section laminate (top and bottom)
Y_{na}	Neutral axis position above bottom
□	Web angle
y	Coordinate measured upward starting at the bottom of the deck (i.e. y=0 @ deck bottom)

Bending Analysis

Maximum Bending Moment (simple supports, 80 psi NO FACTORS)

The bending moment at the center span of a simply supported beam element 24" long (24" between girders), by 9.5" wide (one representative width), under a surface load of 80 psi, is 54720 in-lb. This is slightly higher than the ASHTO tire because the 80 psi covers a width of 24" instead of 20".

Section Elements, Bending stiffness (EI), Neutral Axis position, Bending Stress

The maximum laminate stresses are: +/- 3.9 ksi; compared to +88.6 ksi and -60.0 ksi strength properties. Not a concern.

The maximum grout stresses are: +/- 1.6 ksi; compared to +2.4 ksi and -14.5 ksi strength results. No problem in compression, more of a concern in tension. Details are below.

Table 15. Deck beam analysis summary – no factors.

Deck thickness "h" (in)	4.5		Bending Moment (in-lb)		
Web angle (deg)	68		5.47E+04		
Grout width avg. "Wg" (in)	5.5				
Rep. width "wr" (in)	9.5				
Input Thickness & Modulus				Stress (ksi)	
Deck Region		E (msi)	t (in)	Top	Bottom
Top outer skin	t_{s2}	4.80	0.20	-3.9	-3.5
Top grout	t_g	2.16	1.00	-1.6	-0.8
Top Inner skin	t_{s1}	4.80	0.20	-1.8	-1.5
Top narrow laminate	t_n	4.80	0.20	-3.9	-3.5
Webs	t_w	4.80	0.20	-0.2	0.2
Bottom inner skin	t_{s1}	4.80	0.20	1.5	1.8
Bottom grout	t_g	2.16	1.00	0.8	1.6
Bottom outer skin	t_{s2}	4.80	0.20	3.5	3.9
Bottom narrow laminate	t_n	4.80	0.20	3.5	3.9
Y-neutral axis (in)		2.25		EI (lb-in^2)	1.53E+08

Maximum Bending Moment (simple supports, 80 psi WITH FACTORS)

Bending moment from 2.1 is multiplied by factors of 1.77 and 1.33, to get a total bending moment of: 93400 in-lb.

Section Elements, Bending stiffness (EI), Neutral Axis position, Bending Stress

The maximum laminate stresses are: +/- 6.6 ksi; compared to +88.6 ksi and -60.0 ksi strength properties. Not a concern.

The maximum grout stresses are: +/- 2.7 ksi; compared to +2.4 ksi and -14.5 ksi strength results. No problem in compression, but tension is a concern. A more refined analysis is needed to determine if this is really a problem. Details are below.

Table 16. Deck beam analysis summary – with factors.

Deck thickness "h" (in)	4.5			Bending Moment (in-lb)	
Web angle (deg)	68			9.34E+04	
Grout width avg. "Wg" (in)	5.5				
Rep. width "wr" (in)	9.5				
Input Thickness & Modulus				Stress (ksi)	
Deck Region		E (msi)	t (in)	Top	Bottom
Top outer skin	t_{s2}	4.80	0.20	-6.6	-6.0
Top grout	t_g	2.16	1.00	-2.7	-1.4
Top Inner skin	t_{s1}	4.80	0.20	-3.1	-2.5
Top narrow laminate	t_n	4.80	0.20	-6.6	-6.0
Webs	t_w	4.80	0.20	-0.3	0.3
Bottom inner skin	t_{s1}	4.80	0.20	2.5	3.1
Bottom grout	t_g	2.16	1.00	1.4	2.7
Bottom outer skin	t_{s2}	4.80	0.20	6.0	6.6
Bottom narrow laminate	t_n	4.80	0.20	6.0	6.6
				EI (lb-in^2)	
Y-neutral axis (in)		2.25			1.53E+08

Bending Deflection

The bending stiffness "(EI)" is used to determine the deflection of the simply supported beam with the 80 psi loading. Two cases are considered: 1) simply supported uniform load, and 2) simply supported center load (as though the total load was concentrated at the center).

Table 17. Deflection.

Condition	Center Deflection (in)
Uniform Load	0.021
Center Load	0.034

Web Analysis

Web Shear Stress

The maximum shear load on the beam with a uniform 80 psi applied to a 20" wide by 9.5" wide section, where the 20" direction is just up against a girder (for maximum shear load), 8867 pounds, with a corresponding web shear stress of 6823 psi.

Using load factors of 1.77 and 1.33, the maximum shear load is 20873 pounds, with a corresponding web shear stress of 16062 psi.

Considering a shear strength of 13500 psi, the calculated shear stress is a cause for concern, and a more refined analysis is in order.

Web Compressive Stress

Using a tire width of 20" and a girder width of 6", the web compressive stress under the 80 psi over the 20" by 9.5" area is 6831 psi.

Applying factors of 1.77 and 1.33 the web compressive stress is 16800 psi.

Considering a compressive strength of 35800 psi, the web compressive stress is not cause for concern.

Web Stability (Buckling)

A critical web stress of 39145 psi is calculated using: $$\sigma_{Critical} = \frac{\pi^2 E_{F90} t_w^2 \sin^2(\theta)}{3\left(h - 2t_{s1} - 2t_g - 2t_{s1}\right)^2}$$

Comparing this to a maximum web compressive stress of 16800 psi, stability does not seem to be a problem.