SCAN TEAM REPORT

NCHRP Project 20-68A, Scan 13-03

ADVANCES IN FIBER-REINFORCED POLYMER (FRP) COMPOSITES IN TRANSPORTATION INFRASTRUCTURE

Requested by the
American Association of State Highway and Transportation Officials

Prepared by Scan 13-03 Team
Wayne Frankhauser, Jr. – Scan Team Chair
Jerome O'Connor – Subject Matter Expert

Supported by the
National Cooperative Highway Research Program

Acknowledgments

This study was conducted as part of the National Cooperative Highway Research Program (NCHRP) Project 20-68A, the U.S. Domestic Scan program. This program was requested by the American Association of State Highway and Transportation Officials (AASHTO) through funding provided by NCHRP. Additional support for selected scans is provided by the Federal Highway Administration (FHWA) and other agencies.

The purpose of each scan, and of Project 20-68A as a whole, is to accelerate the integration of innovative ideas into practice by information sharing and technology exchange among state transportation agencies. Experience has shown that personal contact with new ideas and their application is a particularly valuable means for sharing information about practices. A scan entails peer-to-peer discussions between practitioners who have implemented practices of interest and who are able to disseminate knowledge of these practices to other peer agencies. Each scan addresses a single technical topic that is selected by AASHTO and the NCHRP 20-68A Project Panel. Further information on the NCHRP 20-68A U.S. Domestic Scan program is available at http://apps.trb.org/cmsfeed/TRBNet-ProjectDisplay.asp?ProjectID=1570.

This report was prepared by the scan team for Scan 13-03, Advances in Fiber-Reinforced Polymer (FRP) Composites in Transportation Infrastructure. The members of the scan team are listed below. Scan planning and logistics are managed by Arora and Associates, P.C. Harry Capers served as the Principal Investigator. Melissa Jiang provided valuable support to the team. NCHRP Project 20-68A is guided by a technical project panel and managed by Andrew C. Lemer, PhD, NCHRP Senior Program Officer.

The scan team members include the following individuals:

Wayne Frankhauser, Jr., PE, AASHTO Chair, Maine DOT
Jamal Elkaissi, PE, FHWA Structure Team
Steven Kahl, PE, Michigan DOT
Stacy McMillan, PE, Missouri DOT
William (Will) Potter, PE, Florida DOT
David Rister, PE, South Carolina DOT
DeWayne Wilson, PE, Washington State DOT
Jerome O'Connor, PE, University at Buffalo, Subject Matter Expert

Disclaimer

Scan 13-03
Advances in Fiber-Reinforced Polymer (FRP) Composites in Transportation Infrastructure

REQUESTED BY THE

American Association of State Highway and Transportation Officials

PREPARED BY

Wayne Frankhauser, Jr., PE, AASHTO Chair, Maine DOT
Jamal Elkaissi, PE, FHWA Structure Team
Steven Kahl, PE, Michigan DOT
Stacy McMillan, PE, Missouri DOT
William (Will) Potter, PE, Florida DOT
David Rister, PE, South Carolina DOT
DeWayne Wilson, PE, Washington State DOT
Jerome O'Connor, PE, University of Buffalo, Subject Matter Expert

SCAN MANAGEMENT

Arora and Associates, P.C.
Lawrenceville, NJ

July 2015

The information contained in this report was prepared as part of NCHRP Project 20-68A U.S. Domestic Scan, National Cooperative Highway Research Program.

TABLE OF CONTENTS

Table of Contents

List of Appendices

List of Figures

List of Tables

Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACMA	American Composite Manufacturers' Association
AEWC	Advanced Engineered Wood Composites Center (now known as the Advanced Structures & Composites Center) (University of Maine)
AII	AASHTO Innovation Initiative
Anisotropic	Having a physical property that has a different value when measured in different directions
Bond Critical	An application whose effectiveness depends on the integrity of the adhesive bond between FRP laminate and concrete substrate
CFCC	Carbon Fiber Composite Cable
CFRP	Carbon Fiber-Reinforced Polymer
Composite	Any material made up of constituents that retain their own material properties while contributing to the properties of the system as a whole (e.g., reinforced concrete)
Contact Critical	An application whose effectiveness depends on intimate confining contact between FRP laminate and concrete substrate, rather than the bond between them
Curing	A molecular cross-linking process that is sometimes accelerated with the application of heat
DB	Design-Build
DOT	Department of Transportation
FAST Act	Fixing America's Surface Transportation Act (U.S. DOT)
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
Fiber	A long, thin element that provides tensile strength to the FRP composite
FRP	Fiber-Reinforced Polymer A composite material comprised of fibers, a resin matrix, and other additives such as fillers
GFRP	Glass FRP
Glu-lam	Manufactured structural members comprising laminations of timber glued together to form a more massive and efficient member; FRP can be included in the laminations to enhance the performance even more

Hardening	A means of improving security by protecting a structural member with FRP or other material
Hybrid	Two or more different composite materials in the same system (e.g., concrete and FRP)
IBRC	Innovative Bridge Research and Construction (IBRC[1]) (Program) (FHWA) An FHWA funding program established under the Transportation Equity Act for the 21st Century (TEA-21) that served to stimulate the use of FRP materials for bridges; authorized for six years starting in FY 1998, and extending through FY 2005 due to extensions of TEA-21
IBRD	Innovative Bridge Research and Deployment (IBRD) Program (FHWA) A program that followed FHWA's IBRC program[2] with a slightly different emphasis IBRD provided approximately $13 million per year (with $4 million earmarked for high-performance concrete); ran from 2005 until 2012 (except 2008) through SAFETEA-LU and subsequent extension acts
KDOT	Kansas Department of Transportation
MaineDOT	Maine Department of Transportation
Matrix	A structure formed by cured resin, encasing the fibers in a FRP composite
MDOT	Michigan Department of Transportation
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDOR	Nebraska Department of Roads
NHI	National Highway Institute
NSM	Near-Surface Mounted A technique for strengthening concrete structural members by embedding cured FRP bars/strips in adhesive just below the surface after routing a groove
ODOT	Oregon Department of Transportation
P/S	Prestress, Prestressed, Prestressing
PT	Post-Tension, Post-Tensioned, Post-Tensioning
Pultrusion	A continuous process whereby reinforcing fibers are first pulled through a resin bath, then into a shaping and forming guide system and finally into a die where the product is generally heated and cured to its nominal dimensions
PVC	Polyvinyl Chloride
QA/QC	Quality Assurance/Quality Control

1 Innovative Bridge Research Program: Building for the Future, Federal Highway Administration, U.S. Department of Transportation, https://www.fhwa.dot.gov/publications/focus/01feb/innovative.cfm

2 Innovative Bridge Research and Deployment (IBRD) Program, 2012 Discretionary Grant Program Fact Sheets, Special Federal-aid Funding, Federal Highway Administration, U.S. Department of Transportation, http://www.fhwa.dot.gov/discretionary/2012ibrd.cfm

R&D	Research and Development
RC	Reinforced concrete
Resin	A liquid that hardens and cures into a matrix to bond fibers together, protect the fibers, and transfer load among them
RI	Readiness Index
SCOBS, SCOBS T6	Subcommittee on Bridges and Structures, T-6 Fiber Reinforced Polymer Composites (AASHTO)
Service Life	The number of years that a structures is able to be used based on its ability to meet its strength and serviceability requirements
sf	Square Feet
SIP	Stay-in-Place (e.g., SIP concrete forms)
T6	Subcommittee on Bridges and Structures, T-6 Fiber Reinforced Polymer Composites (AASHTO)
Thermoplastic Resin	A polymer compound that becomes soft or fluid when heated and then returns to its original solid state when cooled
Thermoset Resin	A petrochemical derivative that sets permanently once it cures; the process is irreversible (i.e., a cured part cannot be melted and remolded)
TIG	Technology Implementation Group (AASHTO)
TRB	Transportation Research Board
UMaine	The University of Maine
URL	Uniform Resource Locator; a website address
UV	Ultraviolet
VARTM	Vacuum-Assisted Resin Transfer Molding Manufacturing Process A product manufacturing process whereby dry fiber is impregnated with liquid resin by encasing the fiber in plastic, creating a vacuum within the plastic, then letting atmospheric pressure push the resin toward the areas of low pressure
WSDOT	Washington State Department of Transportation
WVDOT	West Virginia Department of Transportation
X'	X Feet
X"	X Inches

Executive Summary

This document summarizes NCHRP 20-68A U.S. Domestic Scan 13-03, Advances in Fiber-Reinforced Polymer (FRP) Composites in Transportation Infrastructure. FRP is not a product; it is a class of material that can be tailored and deployed in different ways to solve infrastructure problems. This report also describes new opportunities that will arise because of FRP's unique properties. To assess the state of practice, in 2015, a team of Department of Transportation structural engineers visited states that have been using FRP for highway structures. These agencies described successful applications; however, they also noted the challenges of deploying a technology without national standards. Project summaries, plans, and specifications were shared and will be made available as a result of this scan.

The team identified cost-effective uses that are ready for deployment on a wider basis, on both existing infrastructure and for new elements and systems. On existing bridges, FRP is becoming a valuable tool for repairing and strengthening concrete members. Particularly appealing to owners is the ability to use FRP when it can provide a relatively quick solution in time-sensitive situations, such as when concrete girders have been hit by an over-height truck. In these cases, repairs can be made within a week or two of the incident. Similarly, a bridge determined to be deficient can be strengthened to avoid closing or load-restricting it, if only for the interim while developing a longer term solution. The team also identified a particular advantage relative to historic bridges, which is that FRP can often be used to extend the service life without significantly altering the appearance of these heritage structures. Thirteen applications for existing bridges were identified.

Being lightweight and corrosion-resistant is an incentive for using FRP for new structural components or even entire bridge systems. Twenty-one types of successful applications were identified and are listed herein.

The team also identified areas where practice could be improved. For example, the team suggests that a means for inspecting FRP as a bridge element be developed so that an inventory and performance history can be generated. Information sharing will benefit others who are interested in the technology. Detailed information about research and past projects can be shared via the web to elevate state-of-the-practice nationwide. Additional training is provided for designers, bridge inspectors, and the maintenance staff who are responsible for oversight and operation of the in-service bridges. Perhaps most important, the key to for owners and their engineers to fully unlock the potential of composite materials are American Association of State Highway and Transportation Officials (AASHTO) guidelines, commentary, and examples for design, construction, inspection, and maintenance. This report includes a preliminary roadmap to show what the scan team thinks is necessary to make more FRP applications practice ready.

1 Introduction

A composite is a material made of two or more constituents that retain their own properties. They do not blend together, but together produce a new material that is superior to any of its individual components. Fiber-reinforced polymer (FRP) is not a product; it is a class of material that can be tailored and deployed in different ways to solve infrastructure problems. FRP's unique properties also present new opportunities. FRP composites typically used in transportation infrastructure comprised glass or carbon fibers embedded in a polymer resin such as vinyl ester or epoxy. The resins used are thermoset, which means that the chemical reaction initiated by a hardener is irreversible. They do not melt when heated as a thermoplastic resin would. Thermoplastics are not the focus of this study; however, since research has led to the construction of several highway structures, additional information on that technology is provided in Appendix K.

There are several different ways to create FRP. One can simply apply liquid resin to a fiber sheet in an impregnation process called hand lay-up. Another method, called pultrusion, is highly automated. In this approach, fibers are continuously drawn through a resin bath and then heated in a dye that shapes and hardens the product. Regardless of the fabrication method, FRP's tensile strength comes from the fibers. Since strength is only in the direction of the fibers, FRP is considered an anisotropic material. The role of the resin matrix is to bind the fibers together so load is shared among the individual fibers and to protect the fibers from damage.

FRP can be designed with fiber layers in multiple directions to provide quasi-isotropic characteristics. The structural properties of any FRP depend on its "fiber architecture" and the resins used. Of course, quality is a major determining factor, too. A properly made FRP will have resin in contact with individual fibers so that it is thoroughly "wet-out" prior to cure.

Overview of the Domestic Scan Program

The study described in this document was conducted as part of NCHRP Project 20-68A, the U.S. Domestic Scan program. The American Association of State Highway and Transportation Officials (AASHTO) requested this study; funding was provided through the National Cooperative Highway Research Program (NCHRP). A technical project panel guides NCHRP Project 20-68A, which is managed by NCHRP Senior Program Officer Andrew C. Lemer, PhD. The NCHRP is supported by annual voluntary contributions from the state departments of transportation (DOTs). The U.S. Federal Highway Administration (FHWA), host agencies, and others provide additional support for the project scans.

The purpose of Project 20-68A is to accelerate beneficial innovation by facilitating information sharing and technology exchange among the states and other transportation agencies and by identifying actionable items of common interest. Experience has shown that personal contact with new ideas and their application is a particularly valuable means for such sharing and exchanging information. A scan entails peer-to-peer discussions between practitioners who have implemented new practices and others who are able to disseminate knowledge of these new practices and their benefits to a broader audience. Each scan addresses a single technical topic that AASHTO and the NCHRP 20-68A Project Panel have selected. Further information on the U.S. Domestic Scan program is available on the web[3].

3 NCHRP 20-68A, US Domestic Scan Program, The National Academies of Sciences, Engineering, and Medicine, Transportation Research Board, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1570

The FRP Domestic Scan

The U.S. Domestic Scan program (NCHRP 20-68A) was funded through the NCHRP at the request of AASHTO. Each domestic scan in this program addresses a single technical topic that has been identified as an area of interest to state DOTs. This document describes a domestic scan that was conducted in 2015 under U.S. Domestic Scan 13-03, Advances in Fiber-Reinforced Polymer (FRP) Composites in Transportation Infrastructure, with an emphasis on bridges and other highway structures.

Rationale

FRP composite materials are commonly used for national defense and in the boating, aerospace, and automotive industries. However, so far, they have not been widely accepted as a standard material in civil engineering practice, a field dominated by steel and concrete. Although researchers have been studying the possibility of using FRP to solve infrastructure problems since the late 1980s, FRP is still not widely accepted in practice. This is despite the apparent benefits (e.g., corrosion resistance) and the proof-of-concept that field demonstrations that have been in service for 15 to 20 years have provided. The underlying motive of this domestic scan is to identify the reasons for civil engineers' inability or reluctance to use FRP as tool for improving existing infrastructure and new construction and address the barriers to the more widespread use of FRP composite materials.

Scope

The team used a desk scan to determine which states to visit and interview, based on time and budget constraints. Although the team was interested in learning about any FRP application that had the potential for use in transportation infrastructure, the primary focus is on bridges and structures.

FRP composite materials are inherently difficult to categorize because the combination of fiber types and architecture, resin formulations, component configurations, and manufacturing methods is virtually limitless. This versatility is generally an asset because it theoretically gives the designer the ability to customize solutions that capitalize on material properties that precisely fit the need.

In practice, however, engineers typically do not have the educational background to tailor FRP materials on a project-by-project basis. They rely heavily on suppliers for assistance. While responsibility for a design ultimately resides with the professional engineer-of-record, many projects have been a collaborative effort between manufacturers and civil engineers. For the purposes of this scan report, it is best to think of FRP as a product or system design engineers use to solve infrastructure problems. As such, potential uses identified during the scan are presented according to their use or the objective of their application (e.g., strengthening concrete to resist shear).

Objectives

The domestic scan program creates an opportunity for DOTs to share their experiences so that others can benefit. The scan team saw FRP applications in the field; observed tests in research labs; listened to case-study presentations; had informal discussions with managers, designers, and inspectors; and collected project information that will be helpful to potential users. The hosts provided supplementary information on the types of FRP applications used, project plans and specifications, materials and bid cost data, performance history, suggestions for improving procedures, lessons learned, and barriers to more widespread use

As a result of its scan, the team is in a position to:

- Assess the performance of past use
- Share success stories; point out problems and knowledge gaps that will require additional investigation
- Identify impediments to adoption of the technology
- Collect and share project summaries, specifications and plans
- Make recommendations for code development, training, quality programs, and other essential aspects of a deployment program

Scan Team

The project's principal investigator made initial contact with host agencies and presented them with amplifying questions developed by the scan team to help agencies provide pertinent information in a consistent manner. A scan coordinator took care of logistics using an itinerary determined by the team members.

The scan team comprised eight members (see Figure 1-1). A biographical sketch and contact information of each member are provided in Appendix A and Appendix B, respectively. Six represented the structures division of state DOTs: Florida, Maine, Michigan, Missouri, South Carolina, and Washington; another member represented FHWA. The team's subject matter expert was from the Institute of Bridge Engineering, University at Buffalo. The team's chair is also the chair of AASHTO's Subcommittee on Bridges and Structures (SCOBS), T-6 Fiber Reinforced Polymer Composites[4], referred to simply as T6.

Figure 1-1 The scan team (left to right): Melissa Jiang (coordinator); DeWayne Wilson; David Rister; Wayne Frankhauser, Jr. (chair); Stacy McMillan; Will Potter; Jerome O'Connor (subject matter expert); Steven Kahl; and Jamal Elkaissi

[4] SCOBS-T-06 Fiber Reinforced Polymer Composites Committee, AASHTO Subcommittee on Bridges and Structures, American Association of State Highway and Transportation Officials, http://bridges.transportation.org/Pages/T-6FiberReinforcedPolymerComposites.aspx

Methodology

Preliminary Desk Scan

A literature search was conducted to get an initial assessment of the types of FRP applications that have been completed, what research has been done, and which states are leading deployment efforts. This helped the scan team plan its site visits and formulate amplifying questions to stimulate in-depth discussions.

Host Agencies and Participants

States were involved in this scan by providing a team member, hosting the scan team in their state, meeting with the team in person, or presenting to them virtually. The states that contributed were Florida, Kansas, Maine, Michigan, Missouri, Nebraska, New York, Ohio, Oregon, Pennsylvania, South Carolina, and Washington (see Figure 1-2).

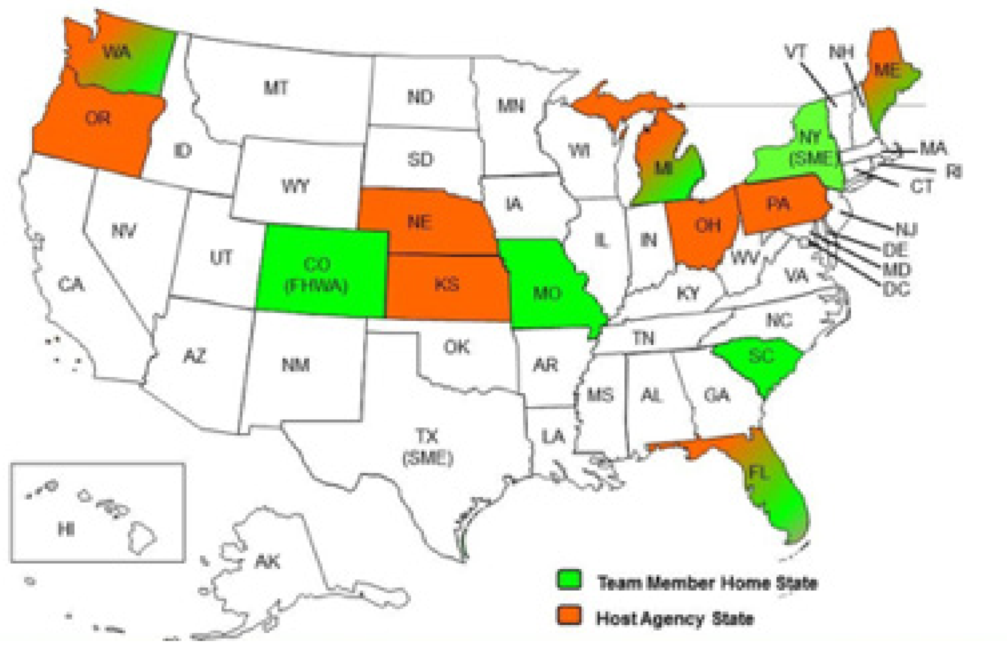


Figure 1-2 States involved in the FRP scan

Travel Scan

Travel was necessary to obtain firsthand information about completed and planned applications. This information was shared with the team via agency presentations; discussions with state DOT employees, their consulting engineers, and researchers; and visual observation of installations in the field. This was supplemented by team members' knowledge of applications in their home states.

The scan itself consisted of two one-week trips. The first trip was from May 31 through June 6, 2015, and involved multiple meetings and site visits in Maine and Florida. The second trip was from July 12 through July 18, 2015, and covered Michigan, Oregon, and Washington State; four additional state DOTs were represented during the second trip using virtual-meeting software or in person. Appendix C provides further detail on the team's itinerary. Appendix D provides host agency key contact information.

Amplifying Questions

Appendix E provides a list of questions that was presented to the host states prior to the scan. The questions were designed to elicit information that the team was interested in and provide a suggested structure for presentations that were developed for the team. Agencies were encouraged to share both good and bad experiences that they have had.

Analysis and Presentation of Findings

Information came from presentations given by host agencies, presentations by invited consultants and researchers, personal dialogue between team members and the contributors, shop tours, field trips, and supplementary project information supplied in the form of plans, specifications, and photos. At the end of each day during the scan, the team met to synthesize their thoughts and impressions of what they had learned and observed. The subject matter expert was responsible for compiling the information for incorporation into this final report.

The following appendices provide additional information that will be useful to the reader:

- Appendix F provides contact information for technical experts or others who can provide additional information on each FRP application.
- Appendix G provides additional information arranged by state and includes links to case studies and other resource material.
- Appendix H gives bid prices obtained in Michigan for an approximation of cost for certain FRP items.
- Appendix I is a preliminary list of action items that may be included in a T6 road map.
- Appendix J is a bibliography that is broken down into the following sections:
    - AASHTO guidance
    - American Concrete Institute (ACI) guidance
    - ASTM tests for FRP
    - National Highway Institute (NHI) training
    - NCHRP research reports (The last section, "Select Research Reports Since 1998, Alphabetical by Author," is provided as a separate file "FRP Bibliography.pdf".)
- Appendix K is "Thermoplastics in Transportation Infrastructure."

Technology Readiness

A primary objective of the scan team is to report on the maturity of the technology. FRP composites have been applied to transportation infrastructure in many different ways. Because of the variety of materials, shapes, and intended functions, it is impossible to describe FRP technology, as a whole, as being mature or not. Each particular use of FRP must be evaluated individually to determine if it is practice ready or only partially so.

The team initially employed descriptions of readiness that the Department of Defense had developed; however, it opted for a simpler approach tailored to the needs of transportation agencies. Although each transportation agency will make its own decision about whether an application is appropriate for use on its structures, the readiness indices (RIs) shown in Table 1-1 are provided as a general guide; Table 1-2 describes each category.

Readiness index	Status of the technology
1	Practice ready
2	Maturing
3	Under development
4	Emerging

Table 1-1 Readiness index

Practice ready (RI = 1)	• The subject has been thoroughly researched; research and development (R&D) is virtually complete. • Design procedures have been validated in the lab and as part of a demonstration project in the field, such that behavior and failure modes are fully understood. • Sufficient guidance exists for design, construction, inspection, maintenance, and repair, including quality assurance/quality control (QA/QC) for each phase. • There have been successful field applications in the US; say, 10 or more. • Performance over time, under service conditions, has been as expected. • Numerous case studies, drawings, specifications, and cost data exist and are available for reference. • Training is available for all phases (ideally National Highway Institute [NHI]). • Expert users and university researchers are available consultation. In summary, applications in this category are ready for deployment because there is sufficient experience to demonstrate their effectiveness and resources are available to support use by other DOTs.
Maturing (RI = 2)	• The subject has been researched adequately and is ready for trial field applications so that it can be evaluated in service conditions over time. • Design procedures have been validated in the lab and as part of a demonstration project in the field, such that behavior and failure modes are generally understood. • Some guidance exists for design, construction, inspection, maintenance, and repair, including QA/QC. Documentation can be considered "working documents" that are subject to revision based on lessons learned from field experience. • There have been some successful field applications in the US; say three or more. • Performance over time, under service conditions, is being evaluated. • There are some case studies, drawings, specifications, and cost data available, but the information is somewhat limited. • Some training is available, but more needs to be developed. • Expert users and university researchers are available for consultation. In summary, applications in this category are generally ready for trial deployment, improvements still can be made to practice and guidance as experience is gained, documented, and shared.
Under development (RI = 3)	• R&D is ongoing. • Validation of design procedures continues to be done by laboratory testing. • A field demonstration project may have been completed. • Guidance still needs to be developed for all phases of the application's life cycle (i.e., design, construction, inspection, maintenance, and repair, including QA/QC for each phase). • Potential performance is being assessed through laboratory testing. • There may be one or two examples of a design with drawings, specifications, and cost data. • Training has yet to be developed. • There are a few expert users and university researchers. In summary, applications in this category are beginning to move from the laboratory to the field, but little support (i.e., past case studies, drawings, specifications, costs, and training) is available to prospective users.
Emerging (RI = 4)	• The application is feasible, but R&D is in the early stages. • Research and analysis are being done to better understand behavior and potential failure modes. • Guidance for design and construction does not exist. • The application has not been demonstrated in the field. • Performance under service conditions has not been evaluated. • Examples of drawings, specifications, or costs are not available to potential users. • Training has not been developed yet. • Few experts are available for consultation. In summary, these uses are conceivable, but additional R&D is necessary because little investigation has been done within the transportation community.

Table 1-2 Readiness index descriptions

Overview of the Scan Team's Findings

The presentations the host states delivered reflected a variety of infrastructure problems with which DOTs are dealing. States are addressing issues that are sometimes unique to the state, because of climate, types of construction used, design details, and other factors. For this reason, each state DOT research program and FRP deployment is naturally tailored to its own particular needs. There are so many ways that FRP can be used that it was necessary to devise a method of grouping them.

For the sake of organization, all uses were first classified into one of two broad categories, existing infrastructure and new construction. Section 2 of this report is dedicated to FRP used to improve existing structures. Section 3 is for new construction, describing FRPs that are used in the construction of new components or systems.

Sections 2 and 3 each include a list of FRP uses. Each use describes the purpose or function according to the customer's need, which may be a particular problem or an opportunity provided by its unique characteristics. No attempt was made to list specific FRP products; if a specific product is named, such reference is not to be taken as any kind of endorsement. State agencies can use the numbering system to fit their past and proposed applications into groups that can be compared with other agencies.

Summary of FRP Usage for Scan Member States

The following is provided to give an overview of the types of projects that DOTs have undertaken. Not all member states are listed because some did not have the information readily available.

Florida

Florida DOT (FDOT) has many concrete structures in a coastal environment that suffer the effects of corrosion. Consequently, FDOT is pursuing research and application of FRP that focuses on reinforced concrete durability. Bridges damaged by over-height vehicular loads and deterioration of bridge fender systems are also problems that have been commonly addressed in Florida using FRP.

Decks	1 appliction (removed from service)
FRP fender systems	22 systems or more are in place (6250 linear feet)
Glass FRP (GFRP) reinforcement/carbon fiber reinforcement	1 pi le jacket application. Standards and specifications are in place to begin implementation. Design Standards for Bearing Piles are published (Index 22600) and Structures Design Guidelines define mandatory use for intermediate pile bents in extremely aggressive locations. A planned project (letting date June 15, 2016) will include hybrid composite (HC) beams, GFRP reinforcement in the deck, a pier cap, and sheet piles, as well as carbon fiber-reinforced polymer (CFRP) in the piles and sheet piles. Two other projects will have GFRP reinforcement in the bulkhead caps.
Near-surface mounted (NSM) repairs using CFRP	3 or more repairs
Repairs to concrete using externally bonded FRP	This is a fully implemented repair procedure that has been used for over 25 years.

Kansas

Kansas DOT (KDOT) has been pursuing the use of FRP materials in bridge applications since 1995. Currently, KDOT makes use of FRP for repair and strengthening applications and is investigating the use of GFRP reinforcing for new construction with a demonstration project comparing a GFRP-reinforced deck to a conventionally reinforced deck at twin structures in an urban interstate location.

Column strengthening with FRP wrap	20 bridges (approximate)
Concrete beam strengthening (RC and prestressed [P/S])	10 bridges (approximate)
Bridge decks with GFRP reinforcement	1 bridge
FRP bridge superstructure	1 bridge
FRP bridge decks	3 bridges (decks have been replaced)

Maine

Maine DOT (MaineDOT) has leveraged the experience of the state's composite boat builders by partnering with university researchers to develop new infrastructure applications such as wood-FRP hybrid beams, concrete-filled FRP arch bridges, and more. A brief summary of the state's use follows.

Bridge drains	10 bridges
CFRP cable stays	1 bridge (used alongside steel)
CFRP transverse post-tensioning (PT)	2 bridges
CFRP P/S	1 bridge
Concrete-filled FRP tube arch	9 bridges
Culvert invert relining with FRP	3 projects
Fender piles	1 bridge
GFRP deck reinforcement	3 bridges and several in design
Hybrid composite beams	4 bridges
Load-bearing piles	4 research trials but not yet deployed
Nonproprietary flexural strengthening system for concrete slabs	Developed but not yet deployed

Michigan

Michigan DOT (MDOT) has also benefited from local research universities. Since the state has a harsh environment for infrastructure, MDOT has supported research to develop corrosion-free prestressing (P/S) tendons and become a leader in this area. Average bid prices for some of the items used in these projects can be found in Appendix H. Michigan has taken the lead on an AASHTO Innovation Initiative[5] (AII, the former AASHTO Technology Implementation Group [TIG]) for CFRP strands. Information can be found at online[6].

CFRP P/S and transverse PT	4 bridges
Column wraps	11 bridges
Beam shear strengthening	2 bridges
FRP reinforcement	1 bridge
Concrete-filled FRP tube arch culvert	3 bridges

5 AASHTO Innovation Initiative (AII), American Association of State Highway and Transportation Officials, http://aii.transportation.org/Pages/default.aspx

6 Carbon Fiber Reinforced Polymer Strands, AASHTO Innovation Initiative, American Association of State Highway and Transportation Officials, http://aii.transportation.org/Pages/Carbon-Fiber-Reinforced-Polymer-Strands.aspx

Missouri

Missouri DOT (MoDOT):

Hybrid composite beams	3 bridges
FRP drainage systems	Standard practice
Repair/retrofit of concrete	Several times; district repair crews have retrofitted concrete columns by bonding FR

Nebraska

Nebraska Department of Roads (NDOR) plans to expand its use of FRP and is currently developing an FRP-reinforced approach slab/paving section standard for optional use. Past projects include:

FRP reinforcement bridge deck	1 bridge
FRP pier cap protection/strengthening	1 pier cap
FRP girder strengthening (shear and flexure)/protection	1 bridge

Oregon

Oregon DOT's (ODOT's) emphasis has been on using FRP to preserve its existing infrastructure. It shows a variety of issues that can be addressed effectively with composite materials.

Arch rib strengthening with CFRP strips	1 bridge
Deck strengthening for rail LL with NSM CFRP rods	4 bridges
Deck strengthening with NSM CFRP rods	4 bridges
GFRP reinforcement (45,000 sq. ft.)	2 bridges
Girder flexure strengthening with CFRP strips	8 bridges
Girder shear strengthening with CFRP strips	32 bridges
Modular FRP bridge decks	4 bridges (state bridges: 9,516 square feet; local bridge owners: 17,200 square feet)
Pier cap flexure strengthening with CFRP strips	1 bridge
Pier cap shear strengthening with CFRP strips	12 bridges

Washington State

As of 2015, Washington State DOT's (WSDOT's) use of FRP included the following.

WSDOT Evaluation Project - Installed FRP on six single columns; contract 5200 (1997)	1 bridge
WSDOT Experimental Feature Project - Column seismic retrofit using three different FRP systems; contract 5509 (1998)	4 bridges
Br 90/52 - FRP wrap of flared single columns and Bridge 90/56: Cut column bars to capacity protect the superstructure, then wrapped hinge area with FRP; contract 7622 (2008)	4 bridges
Bridge 520/25N - Strengthened box girder crossbeam with FRP; contract 7925 (2010)	2 bridges
Wrapped cruciform shaped columns with FRP using FRP anchors at inside corners and placed FRP on crossbeams to prevent concrete debris from falling; contract 8080 (2011)	1 bridge
Superstructure strengthening of US-2 bridges; Phase 1 (2006) and Phase 2 (2008)	
Superstructure strengthening of Alaskan Way Viaduct bridges after Nisqually Earthquake (2005)	
Washington State University research project on FRP retrofitted columns for seismic (2010)	

Cost-Effective Uses

Over the course of the scan, numerous cost-effective uses for FRP were identified. Perhaps most appealing are applications that provide an immediate solution to bridge owners in time-sensitive situations, such as when concrete girders have been hit by an over-height truck. Often, it is not desirable to close or load-restrict a bridge while developing a long-term strategy because traffic congestion and economic disadvantage to local businesses often immediately ensues. Using FRP, it may be feasible to repair damaged girders within a few days as a short-term solution until a long-term strategy can be implemented or as a permanent repair.

The team also identified a particular advantage relative to heritage structures. FRP often can be used to repair and extend service life without significantly altering the appearance. The corrosion-resistant and lightweight nature of FRP provides incentive to use it for new structural components or even entire bridge systems. Examples of FRP uses that DOTs have found to be cost-effective are provided in Appendix G.

Need for Improvement

The team also identified areas where practice could be improved. An inventory of FRP projects and their performance history would be beneficial to others interested in the technology. In addition to a simple inventory, detailed information about past projects could be shared among all potential users to elevate the state of the practice nationwide.

The need to track the performance of past projects is recognized in the Fixing America's Surface Transportation Act[7] (FAST Act), which was passed in late 2015. Section 1422 of that law, entitled Study on Performance of Bridges[8], requires the evaluation of 300+ bridges that were funded under the IBRC program between 1999 and 2004; half of them used FRP material. Their performance will be compared to that of conventionally constructed bridges to document to Congress how the lifecycle costs of bridges can be reduced with the use of innovative materials and technologies.

Training is needed for bridge inspectors and the maintenance staff who are responsible for taking care of bridges. Perhaps, most importantly, AASHTO guidelines, commentary, and examples are needed for design, construction, and maintenance before the use of the material can fully mature and increase in use.

7 Fixing America's Surface Transportation Act or "FAST Act," Federal Highway Administration, U.S. Department of Transportation, https://www.fhwa.dot.gov/fastact/

8 FAST Act Section 1422 Study on Performance of Bridges, Federal Register, https://www.federalregister.gov/documents/2016/11/16/2016-27504/fast-act-section-1422-study-on-performance-of-bridges

Discussions with engineers revealed that there are technical issues that merit more discussion or clarification. Some specific issues, in no particular order, are:

- Develop training, particularly how to design with FRP.
- Determine how performance will be defined.
- Determine a method for assessing durability.
- Emphasize that careful consideration should be given before wrapping chloride-contaminated concrete. Generally, the practice is advised against; however, but in an emergency situation, it may be necessary to consider as a short-term solution.
- Communicate the limitations, restrictions, or range of applicability of each application.
- Stress that there is a maximum allowable thickness (i.e., the maximum number of layers) in a laminate used for repair. More is not better; it just changes the mode of failure.
- Verify the appropriateness of environmental factors used for FRP design.
- Conduct crash testing if GFRP reinforcement is to be used for connecting concrete barrier to concrete decks.
- Understand that an empirical design for GFRP reinforcement in a deck would make it easier to include GFRP bars in a project. The commentary of AASHTO's guide specifications for FRP-reinforced decks refers to the empirical design used in Canada for GFRP; however, AASHTO has not yet evaluated or adopted it.
- Determine if current AASHTO procedures are appropriate for strengthening P/S concrete with CFRP. If the procedures are intended for more than reinforced concrete, they may need to be updated.
- Determine what the maximum allowable limits of improvement should be when strengthening with FRP (e.g., 25% or 50%).
- Address the risk of fire and whether it is small enough to accept, since the risk is not any more than it is for steel and concrete. AASHTO may want to discuss this issue and offer guidance.
- Emphasize that, even though GFRP is corrosion-resistant, when used in a deck, adequate concrete cover will still be needed because of serviceability, construction tolerances, and adverse effects of transverse thermal expansion of GFRP reinforcements.
- Emphasize that an FRP repair to concrete can fail due to accidental damage or vandalism. For this reason, it is important that the structure in its deteriorated condition can handle the dead load and minimal live load without the FRP. Although this concept is incorporated into the AASHTO guide specifications, a consensus on specific criteria to account for this issue would eliminate the current discrepancy in the way designers interpret the meaning of the guidance. In addition, training should always emphasize the importance of this requirement.

Technology Maturity

The scan revealed that it is not possible to generalize about the maturity of FRP technology as a whole because of the wide range of material types, uses, designs, research done, experience level, and other factors. Instead, the team assigned a readiness index (RI) (as defined in Table 11 and Table 12) to individual FRP applications. The indices shown are a consensus of the scan team; however, the RIs should be considered proposed values that are subject to discretion of the owner, since judgment and subjectivity was involved in making a decision about the values. Some of the factors considered were:

- The degree to which research and development (R&D) is considered complete
- The validation of the design model that has been done by component and system prototype testing
- The availability of AASHTO design specifications, guidelines, or other guidance, such as
  - ACI guidance
  - Construction specifications
  - Demonstration project(s) and successful field applications
  - Performance under actual service conditions
  - Availability of training for design, construction, maintenance, inspection, and repair

The scan team understands that some of these items must be developed in parallel with trial uses, since experience helps improve practice and case studies will facilitate the development of training materials.

Risk

The risk associated with using a new technology depends not only on the particular application's maturity, but also on site conditions and many other factors that the owner (e.g., DOT) needs to evaluate. Although this list is not all-inclusive, the possibility of one or more of the following is sometimes cited as a risk:

- Ineffectiveness
- Premature failure
- Injury
- Unanticipated maintenance
- Reduced access for inspection of substrate surfaces

These concerns can be mitigated by selecting sites for demonstration projects that are on redundant routes (i.e., those with a short detour) or a road with low traffic volume. This will be convenient for monitoring performance and should help minimize the repercussions if additional maintenance or attention is required.

However, one does not always get to choose where the need for FRP is. When considering FRP for use on a bridge, care should be given to avoid situations that might cause severe traffic disruption should unanticipated repair or maintenance be required. For instance, if a concrete bridge's low clearance results in it being hit frequently by trucks, an FRP strengthening would be ill advised because the repair would be susceptible to repeated damage. Prudent design will preclude the use of composites in a manner that might result in a sudden or catastrophic failure. Generally, the risk is low for nonstructural applications or ones where failure would progress slowly. In the scenario above where a bridge is hit frequently, FRP may help reduce risk by maintaining the system's/girder's integrity and preventing concrete from falling on traffic below. The FRP assists in holding the section together after the frequent hits.

It is important for the bridge owner and designer to realize that each FRP system is unique and will have certain structural response characteristics depending on the fiber architecture, resin type, manufacturing process, and adherence to a documented quality plan during design and construction. Just as a mix design is needed for each concrete batch, the constituent types and quantities used in an FRP system must be specified and followed precisely. Care must be taken to ensure that unauthorized substitutions are not made to the approved materials and design during construction.

2 FRP for Existing Infrastructure

FRP composites have been shown to be extremely advantageous for correcting deficiencies in existing structures. Due to their intrinsic nature, FRP can be thought of as a new way to provide tensile reinforcement, even external to a structural member. This ability opens up numerous possibilities and potential applications. When evaluating possible uses, it is important to remember that many design variations are possible for any application and future ones are yet to be devised. A technology may be considered practice-ready if at least one system is available.

Table 2-1 lists the applications for existing infrastructure that have been identified. The identification numbers (1 through 14), proceeded by an “E” for “existing”, are assigned for ease of reference and tracking. The corresponding RI indicates the maturity level of each use, as described in Technology Readiness. The RI values presented below can be used as a tool for decision-making, with the recognition that they are only intended to be a guide. The appropriateness of using each technology in any given situation is a matter of judgment on the owner’s part.

Table 2-1 groups the FRP uses by substrate material (E1-E8 for concrete, E9-E12 for metal, and E13 for timber). The list is not intended to exclude any potential application, but suffices as a list of the most common or contemplated ones. A brief introduction to each application is provided in the next section of this report, Repair and Strengthening of Concrete.

FRP Use	RI*
E1. Repair of impact-damaged concrete (reinforced or prestressed)	1
E2. Repair of corrosion-damaged concrete	1
E3. Seismic retrofit of concrete	1
E4. Protective wrapping of concrete	1
E5. Strengthening concrete with externally bonded FRP	1
E6. Strengthening concrete with near-surface mounted (NSM) FRP	1
E7. Strengthening concrete with FRP post-tensioning	2
E8. Strengthening concrete with mechanically-fastened FRP	4
E9. Strengthening structural steel with FRP post-tensioning	4
E10. Culvert liner	2
E11. Repair of impact-damaged metal poles	3
E12. Repair of fatigue-damaged aluminum overhead sign structures	2
E13. Repair and strengthening of timber	2
E14. Other	-

*1 = Practice ready, 2 = Maturing, 3 = Under development, 4 = Emerging; Refer to Table 12 for descriptions of each RI.

Table 2-1 FRP uses and RI for existing infrastructure

Repair and Strengthening of Concrete

One of the fastest growing uses of FRP for civil infrastructure is for the repair, strengthening, and preservation of existing concrete, which can be either conventionally reinforced or P/S. ACI Technical Committee 440[9] and others have guided research and development of applications that use FRP as externally bonded and near-surface mounted (NSM) reinforcement. P/S applications have also been devised. Structural engineers have repeatedly demonstrated its use as supplemental reinforcement and have turned to it as a solution to numerous problems that they face. As the use of FRP increases, it increases awareness and helps it become more accepted by the broader community as a viable construction material.

Drawing from the extensive research and experience that has been done over the past 25+ years, NHI has recently rolled out three web-based training courses related to bonded repairs:

- FHWA-NHI-130105A, Introduction to FRP Materials and Applications for Concrete Structures[10]
- FHWA-NHI-130105B, Construction Procedures and Specifications for Bonded Repair and Retrofit of Concrete Structures[11]
- FHWA-NHI-130105C, Quality Control of Repair and Retrofit of Concrete Structures Using FRP Composites[12]

Documentation of past successes and detailed instructions on how to duplicate that success enables engineers to confidently design repairs for concrete girders that have been damaged by vehicular impact, to improve a substructure's seismic performance, to strengthen a concrete member that needs greater capacity, and to provide environmental protection or rehabilitate corrosion-damaged concrete.

E1. Repair of impact-damaged concrete (reinforced or prestressed)

Available Guidance

AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[13]

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[14]

All too frequently, bridges over roadways get are by over-height trucks or loads. The extent of damage to the concrete depends on the truck height, mass, and speed, among other factors. Usually, the fascia beam is most damaged; however, frequently other beams will also need repair. Figure 2-1.

9 440 – Fiber-Reinforced Polymer Reinforcement Committee, American Concrete Institute, https://www.concrete.org/committees/directoryofcommittees/acommitteehome.aspx?committee_code=0000440-00

10 Introduction to FRP Materials and Applications for Concrete Structures, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, http://www.nhi.fhwa.dot.gov/training/course_search.aspx?course_no=130105A&sf=1

11 Construction Procedures and Specifications for Bonded Repair and Retrofit of Concrete Structures, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, https://www.nhi.fhwa.dot.gov/training/course_search.aspx?tab=0&key=130105B&course_no=130105B&sf=1

12 Quality Control of Repair and Retrofit of Concrete Structures Using FRP Composites, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, http://www.nhi.fhwa.dot.gov/training/course_search.aspx?sf=0&course_no=130105C

13 Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 1st Edition, American Association of State Highway and Transportation Officials, https://bookstore.transportation.org/collection_detail.aspx?ID=118

14 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, American Concrete Institute, https://www.concrete.org/store/productdetail.aspx?ItemID=440208

Figure 2-1 An impact-damaged bridge before (left) and after (right) being repaired with bonded CFRP

Dozens of bridges have been restored to service using FRP, with little disruption to traffic. Using proven and well-accepted techniques, damaged concrete in structural members can be replaced, then strengthened externally by bonding composite materials to the surface. Carbon fiber is typically used because its tensile strength and modulus of elasticity is higher than glass fiber or other alternatives. In the case of damaged P/S concrete members, the P/S strands should be repaired using mechanical means prior to externally bonding FRP.

Repairs to damaged concrete members can usually be repaired "under traffic" (i.e., without removing the live loads from vehicles) because the cross-linking of polymers occurs over time and is not affected by short-term changes in loading. The bond between the FRP and substrate is not sensitive to traffic loading. If the damage is significant, the live load would need to be minimized, shifted, or removed during the repair.

In some instances, load tests have been conducted after repairs to demonstrate that the load capacity of the member has indeed increased due to the addition of external FRP reinforcing. CFRP sheets are typically used but reinforcement can also be added as NSM.

Florida has led the way developing procedures for the repair of concrete girders with externally bonded FRP. FDOT developed procedures over 25 years ago and now uses the technique routinely. It is a fully implemented repair procedure that is frequently used if an over-height truck strikes a bridge.

The basic steps for performing a bonded FRP repair are illustrated in Figure 2-2 through Figure 2-7. Before starting, one must assess the damage to determine the suitability of this technique. Experience and judgment are needed because there is no specific set of criteria to use when deciding what is repairable. The steps are:

- Repair reinforcement and/or P/S
- Form and replace the damaged concrete to restore the original section and let cure
- Prepare the concrete by cleaning and smoothing rough edges
- Follow the manufacturer's recommended installment procedure when bonding and applying ultraviolet (UV) radiation protective coating

Figure 2-2 Impact-damaged P/S girders

Figure 2-3 Formwork preparation for replacing the damaged concrete

Figure 2-4 Placing concrete to restore the concrete section

Figure 2-5 Restored section, prior to removing the forms

Figure 2-6 CFRP bonded to the repaired concrete section

Figure 2-7 Finished repaire, after applying UV radiation protective coating

E2. Repair of corrosion-damaged concrete

Available Guidance

AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[12]

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[13]

Chlorides from road de-icing salts or saltwater environments accelerate corrosion, reducing the capacity of the structural element. When dealing with corrosion-damaged concrete, care must be taken so as not to worsen, create, or hide any internal problems, especially when the repairs are intended to be a long-term solution. Sound concrete is necessary for bond-critical repairs since their integrity depends on the quality of the concrete substrate and the resulting bond between the concrete and FRP laminate. This most often requires complete removal and replacement of the corrosion-damaged concrete. Theoretically, electrochemical chloride extraction could be considered, but the usual approach is to remove and replace.

In contact-critical applications, the FRP's effectiveness depends on intimate confining contact between FRP laminate and concrete substrate, rather than on the bond between them.

Aside from the need to mitigate chloride contamination, the same techniques can be used to repair corrosion-damaged concrete as impact-damaged concrete. An FRP wrap of a column has the benefits of not only providing confining tensile reinforcement to the concrete, but protection from the elements as well.

Detailed procedures and specifications are available for this remedial work in AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements and Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures; NHI training courses provide additional guidance. A general overview of the process follows as an introduction.

Repair Procedure

- Remove all deteriorated and chloride-contaminated concrete.
- Clean the damaged structural member.
- Assess the extent of damage.
- Repair or replace the steel reinforcement and P/S, if any.
- Provide corrosion protection to existing reinforcement.
- Restore the cross-section by forming and inserting mechanical anchors to enhance the interface between old and new concrete.
- Place new concrete.
- Prepare the concrete for FRP by smoothing rough edges, rounding sharp corners, and cleaning.
- Apply the FRP per design (material type and weight, number of layers, and fiber orientation).
- Add a UV protective coating.
- At the discretion of the owner, a live load test can be conducted after the repair is done.

See Figure 2-8 and Figure 2-9 for before and after images of bonded CFRP repair of corrosion-damaged concrete beams. See Figure 2-10 through Figure 2-13 for before and after images of a CFRP repair made to the underside of a bridge that had spalled concrete and exposed corroded steel.

Figure 2-8 Corrosion-damaged concrete beams

Figure 2-9 Bonded CFRP repair of beams shown at left

Figure 2-10 Elevation view of bridge in proximity to salt water (Brown's Creek, Jacksonville, FL)

Figure 2-11 Spalled concrete and corroded steel on underside of the bridge shown in Figure 2-10

Figure 2-12 Spalled concrete and corroded steel

Figure 2-13 Underside of box beams after repair with bonded CFRP

E3. Seismic retrofit of concrete

Available Guidance

AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[12]

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[13]

Concrete columns, caps, piers, and bents are typical bridge substructure elements. The performance of these members is important because they are so critical to a bridge's resiliency under seismic loading (see Figure 2-14 and Figure 2-15). Substructures are sometimes retrofitted to compensate for the as-built steel reinforcement when it is likely that the design will not provide adequate protection in an earthquake. Deficiencies might arise from details in steel bar lap length, embedment length, or spacing of confinement bars.

Figure 2-14 Shear failure of a concrete bent due to seismic loading

Figure 2-15 Primary steel, buckled during an earthquake due to insufficient lateral confinement

The strength and stiffness of a substructure unit such as a column can often be enhanced by jacketing it with FRP to provide additional confinement and orienting fibers longitudinally to improve flexural capacity.

The potential for shear failure in the member or in column to beam joints, can be reduced. Deficiencies in lap splices can also be remedied by strategically laminating with FRP. It is desirable to have ductility in a reinforced concrete member to avoid the possibility of brittle fracture. Although FRP materials themselves are linear elastic until failure, it has been shown that adding FRP to concrete can provide the combined system with a ductile behavior.

Although steel jackets can provide many of the same benefits, FRP is usually easier to install, can accommodate unusual or non-uniform cross-section shapes such as tapers, and is visually unobtrusive (see Figure 2-16 through Figure 2-18).

Figure 2-16 Concrete column wrapped with CFRP, prior to application of UV protective coating

Figure 2-17 Wrapping round concrete columns with CFRP to improve seismic performance by providing additional confinement

Figure 2-18 Wrapping a square concrete column with CFRP after rounding sharp corners

Since the FRP will change the flexural characteristics of a substructure, care must be taken to properly design the retrofit. For example, although not immediately intuitive, the addition of additional layers of FRP does not proportionally increase strength; in fact, it may decrease it and change the failure mode. Ultimate failure can occur due to tensile failure of the FRP laminate, debonding from the substrate, or fracturing of the concrete substrate beneath the bond line.

E4. Protective wrapping of concrete

> ***Available Guidance***
>
> AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[12]
>
> ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[13]

FRP can provide protection from the deleterious effects of the natural environment. The technique for protecting concrete from the elements is very similar to the previously described applications; however, the FRP wrap's function is merely to preserve the integrity of the concrete. By keeping water and chlorides from migrating into the concrete, the service life of the member can likely be extended. See Figure 2-19 through Figure 2-21.

Figure 2-19 Concrete bent damaged by exposure to salt water

Figure 2-20 A concrete column in the median of a highway that has deteriorated due to salt spray

Figure 2-21 The column shown in Figure 2-20 after repair and protective wrapping with GFRP

E5. Strengthening concrete with externally bonded FRP

Available Guidance

AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[12]

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[13]

Sound concrete can be strengthened with FRP, most often with carbon fiber, by externally bonding sheets or pre-cured laminates to the concrete (see Figure 2-22 and Figure 2-23). When added to a beam or slab, FRP provides tensile strength, thereby improving the member's flexural behavior. This is useful if, for some reason, the concrete member was improperly designed and was under-reinforced. It may also be necessary if the actual loads being experienced are higher than those assumed during design.

Figure 2-22 Bonding pre-cured CFRP strips to the underside of a concrete slab to increase its flexural capacity

Figure 2-23 Elevation of a bridge that has had CFRP strips added to increase the reinforced concrete's shear strength

To ensure a quality product, proper preparation of the concrete surface is essential. It must be clean, dry, and free of laitance that might weaken the bond. Typically, a primer is used to fill and seal small cracks and pores.

Full strength of the bond and laminate is usually reached within 24 hours; however, this depends on the specific product used. It is important to use one manufacturer's components that have been tested for effectiveness as a complete system and not to mix and match components from various manufacturers. Various fibers and resins cannot be used interchangeably. Products must be prequalified prior to use in the field.

E6. Strengthening concrete with near-surface mounted (NSM) FRP

Available Guidance

AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements[12]

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures[13]

This method is similar to a bonded repair. However, instead of laminating FRP onto the surface of the concrete, grooves are cut in the concrete and rods or strips, typically carbon, are embedded in epoxy (or other approved material) beneath the concrete surface (see Figure 2-24). This technique offers protection from abrasion, in contrast to a bonded laminate that is exposed to potential scraping and damage. For this reason, NSM FRP is attractive for use on the top side of concrete decks that are subjected to negative moment, such as over piers and on deck overhangs. NSM FRP may also be used to make P/S repairs.

Figure 2-24 FRP reinforcing bars encased in adhesive as part of a NSM concrete strengthening system. (Note that this is in a laboratory setting.)

E7. Strengthening concrete with FRP post-tensioning

Available Guidance

440.4R-04 Prestressing Concrete Structures with FRP Tendons[15]

[15] 440.4R-04 Prestressing Concrete Structures with FRP Tendons (Reapproved 2011), American Concrete Institute, https://www.concrete.org/store/productdetail.aspx?ItemID=440404

Existing structures are sometimes post-tensioned (PT) to increase capacity (see Figure 2-25 and Figure 2-26). While this can be done with steel tendons, FRP is much lighter and needs no corrosion protection. Because of its low coefficient of thermal expansion, FRP is also less affected by temperature changes. Carbon- or aramid-fiber FRP is most feasible for this application. "Glass fibers have poor resistance to creep under sustained loads and are more susceptible to alkaline degradation than carbon and aramid fibers."[14]

Figure 2-25 CFRP cable and end grip used for P/S

Figure 2-26 Transverse CFRP post-tensioning of concrete beams

E8. Strengthening concrete with mechanically-fastened FRP

Available Guidance

Rapid Strengthening of Reinforced Concrete Bridges[16]

Bonding FRP to concrete is by far the most prevalent method for strengthening a concrete beam in flexure, but powder-actuated tools or wedge anchors have also been used to affix auxiliary load-carrying elements to bridges. Mechanically fastened FRP systems are attractive because workers can rapidly install the systems with minimal training and with common tools. The reinforcement can be added without the extensive surface preparation that bonded systems require and there is no need to wait for materials to cure (see Figure 2-27 through Figure 2-29). Strengthening can be done without closing the bridge to traffic.

Figure 2-27 Mechanically fastened FRP strips

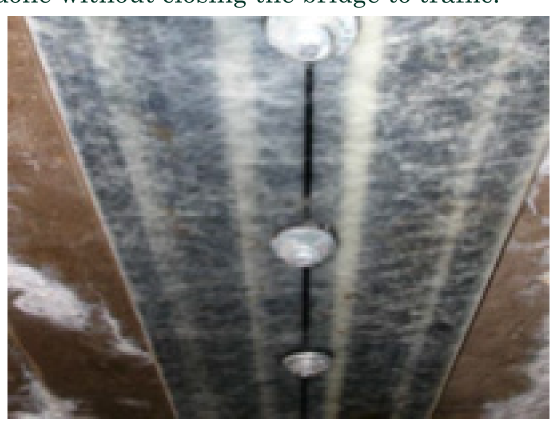


Figure 2-28 Mechanically fastened FRP strip

16 Bank LC, et al., UTC-R64: Rapid Strengthening of Reinforced Concrete Bridges, Center for Infrastructure Engineering Studies, University Transportation Center Program at The University of Missouri – Rolla, December 2002, http://transportation.mst.edu/media/research/transportation/documents/064-cr.pdf

Figure 2-29 A concrete slab strengthened with mechanically fastened FRP strips

Photos courtesy of Bank LC, et al., UTC-R64: Rapid Strengthening of Reinforced Concrete Bridges[15]

The U.S. Army Engineer Research and Development Center has funded R&D. Laboratory research was conducted at the Center's test laboratories and at the University of Wisconsin Structures and Materials Testing Laboratory. Bridge demonstration projects were conducted in Wisconsin and Missouri.

An example of a product used for this technique can be found online[17].

Repair of Metal and Wood Structures

The majority of research related to civil structures has focused on applications that enhance the behavior of concrete. In the future, more uses that apply to metal or wood structures may be developed. Following are some current uses; however, much less guidance exists in this area than for using FRP with concrete structures.

E9. Strengthening structural steel with FRP post-tensioning

Available Guidance

Strengthening of Steel Girder Bridges Using FRP[18]

A large number of bridges use steel for the superstructure or substructure. Although not common practice, there may be situations where FRP may be useful for strengthening steel members that have been compromised by age, fatigue, or corrosion. While there is data on the PT members, not many case studies exist for engineers to use as a guide should they want to consider this rehabilitation option. Figure 2-30 and Figure 2-31 illustrate this application.

18 Phares BM and TJ Wipf, et al., Strengthening of Steel Girder Bridges Using FRP, Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2003. © 2003 by Iowa State University, http://www.iowadot.gov/bridge/ibrc_projects/frp_tension_paper.pdf

Figure 2-30 300 ksi CFRP rods (3/8Ð) being jacked to post-tension a steel girder

Figure 2-31 Post-tensioning with CFRP

Photos courtesy of Phares BM and TJ Wipf, et al., Strengthening of Steel Girder Bridges Using FRP[19]

E10. Culvert liner

Since much of the nation's infrastructure was built over 50 years ago, the effects of corrosion and abrasion have taken a toll on metal culverts. FRP has been used to restore deteriorated inverts or reline the entire cross-section. Repairs like these have an advantage over replacing the culverts because the work can be done without having to open-cut and disrupt traffic. The FRP liner can be engineered to be a load-carrying structural component, with grout fill occupying the annular ring between the old and new materials (see Figure 2-32 through Figure 2-34).

Figure 2-32 Prefabricated FRP arch sections can be slid into an existing culvert, then grout added between them to transfer load to the FRP

Figure 2-33 One method of relining an existing culvert is to use precured FRP sheets

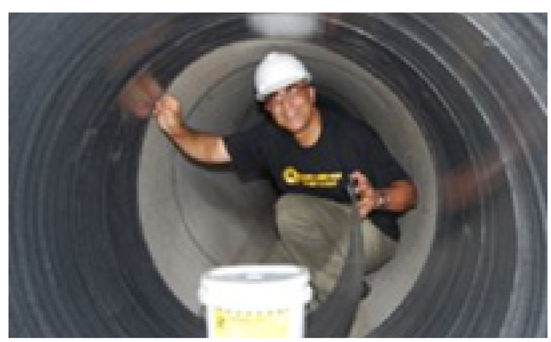


Figure 2-34 Figure 2-33 in its finished state

Photos courtesy of Ehsani MR, FRP super laminates present unparalleled solutions to old problems[19]

[19] Ehsani MR, FRP super laminates present unparalleled solutions to old problems, REINFORCEDplastics, August/September 2009, p 40-45, http://pilemedic.com/pdfs/FRP-super-laminates-present-unparalleled-solutions-to-old-problems.pdf

Maine has been using FRP composites for relining culvert inverts for over 15 years. It works well as an alternative to the traditional use of concrete or shotcrete to line corroded inverts. The process is to clean the bottom of the pipe, nail FRP shell to the pipe walls, and then grout the fill between the shell and the corrugated metal pipe.

E11. Repair of impact-damaged metal poles

The scan team discovered an interest in using FRP to repair metal structures that have been damaged by impacts. The FRP material works well in reshaping the section to achieve the original profile. The strength of the section is brought to the original strength or greater. Research in Florida has shown great promise with this repair technique. The final report to the FDOT research can be found online.[20]

Figure 2-35 through Figure 2-38 illustrate the steps used in the FRP repair of an impact-damaged metal pole.

Figure 2-35 An impact-damaged metal pole

Figure 2-36 The dented area has been smoothed using epoxy filler; horizontal lines mark where FRP will be applied.

[20] Wagner D, KR Mackie, et al., Repair of Impact Damaged Utility Poles With Fiber Reinforced Polymers (FRP), Phase II, Structural Research, Department of Civil, Environmental & Construction Engineering, University of Central Florida, June 2015, http://www.fdot.gov/structures/structuresresearchcenter/Final%20Reports/2015/FDOT-BDV24-977-04-rpt.pdf

Figure 2-37 GFRP wrap being applied

Figure 2-38 Completed pole repair

E12. Repair of fatigue-damaged aluminum overhead sign structures

Available Guidance

Pavement Preservation Concepts and Techniques

Guidelines for the Installation, Inspection, Maintenance and Repair of Structural Supports for Highway Signs, Luminaries, and Traffic Signals[21]

Over 10 years ago, AASHTO designated this application as market-ready and started a TIG to deploy it to state DOTs. Trainers showed DOT personnel in interested states how to prepare the metal and apply an FRP wrap to carry tensile stressing across cracked joints in tubular aluminum sign structures (see Figure 2-39 through Figure 2-42). These repairs have lasted much longer than originally anticipated and have provided the states with time to replace fatigue-damaged structures using routine contract procedures, instead of having to replace them in an emergency. These repairs reduced the risk that a road user could be harmed by a falling sign support. The work can be performed in less than a day by a small crew and for a relatively low material cost.

21 Guidelines for the Installation, Inspection, Maintenance and Repair of Structural Supports for Highway Signs, Luminaries, and Traffic Signals, Bridges & Structures, Federal Highway Administration, U.S. Department of Transportation, https://www.fhwa.dot.gov/bridge/signinspection04.cfm

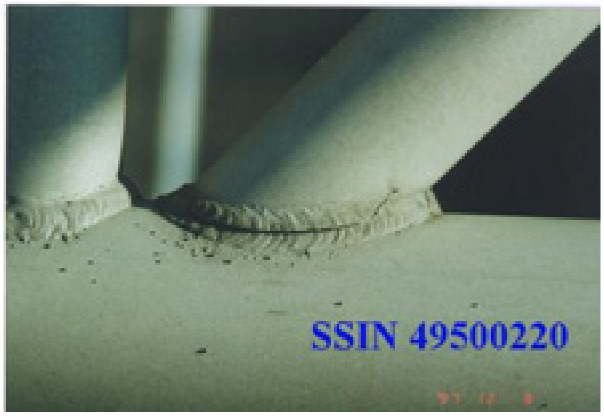


Figure 2-39 Cracked weld in an overhead tubular sign truss

Figure 2-40 Meticulous cleaning (i.e., acid etching) is needed for an FRP repair.

Figure 2-41 Wrapping the joint with FRP according to the manufacturer's recommended procedures

Figure 2-42 The bandaged truss after return to service

Since 2003, FRP has been used as a repair method for cracks in overhead sign structures. New York and Utah DOTs collaborated on research that proved that a FRP-wrapped truss joint was as strong as a fully welded joint and improved fatigue resistance in cracked tubular secondary members. The DOTs developed a specification for the repair procedure, which requires meticulous cleaning of the base metal before application of the FRP material. The work, which includes scrubbing, acid etching, water rinsing, and air-drying, should only be performed by an individual who has been trained and approved by the supplier of the specific product being used. Weather conditions and surface preparation are critical. The cure time is approximately one hour. When applied properly, the specification provides for the restoration of tensile capacity in truss diagonals of overhead sign trusses. An AASHTO TIG was formed to provide hands-on training to installation crews.

The combination of research, specifications, demonstration projects, and training qualifies this application as practice ready (RI = 1). It has been used to guard against structural failure by arresting cracks and preventing fracture of the element.

According to FHWA, the benefits of this technology are threefold:

- It costs less than replacing the full structural sign support structure. A typical repair costs $3,000 per joint.
- It allows repairs to be done quickly. A typical repair takes three workers three hours to complete.

- It causes less traffic disruption because only the lanes beneath the repair need to be blocked off.

E13. Repair and strengthening of timber

Available Guidance

Strengthening Historic Covered Bridges to Carry Modern Traffic[22]

Timber has been used extensively for railroad bridges, in marine piling, and, to a lesser extent, in roadway bridges. Being of plant origin, wood itself is a composite material. Resin can be injected to fill voids and restore rotted timber to a solid mass. An exterior FRP wrap adds axial and flexural strength on par with the wood's original capacity.

GFRP has been used to rehabilitate timber stringers on a railroad bridge. Rehabilitation and load testing were carried out on an open-deck-timber railroad bridge built during early 1900s on the Moorefield, WV, South Branch Valley Railroad, which is owned by West Virginia DOT (WVDOT). Specifically, field rehabilitation involved repairing piles using GFRP composite wraps and phenolic formaldehyde adhesives. Using an 80-ton locomotive, static and dynamic tests were performed to determine the dynamic response of the substructure. Results were a 43% strain reduction in the piles and a 46% strain reduction in the pile cap.

As reported in the May 2016 Research Report No. FHWA-ICT-16-011[23], the FRP-strengthened timber piles specimens performed considerably better than comparable unreinforced timber piles. The FRP wraps significantly improved both strength and ductility. See Figure 2-43 through Figure 2-48.

Figure 2-43 FRP-repaired pile cap

Figure 2-44 FRP-repaired timber piles and stringers

22 Strengthening Historic Covered Bridges to Carry Modern Traffic, FHWA-HRT-07-041, Federal Highway Administration, U.S. Department of Transportation, https://www.fhwa.dot.gov/publications/research/infrastructure/bridge/07041/07041.pdf

23 Kim KH and B Andrawes, Load Rating and FRP Retrofitting of Bridge Abutment Timber Piles, Research Report No. FHWA-ICT-16-011, University of Illinois at Urbana-Champaign, Illinois Center for Transportation, May 2016, https://apps.ict.illinois.edu/projects/getfile.asp?id=4931

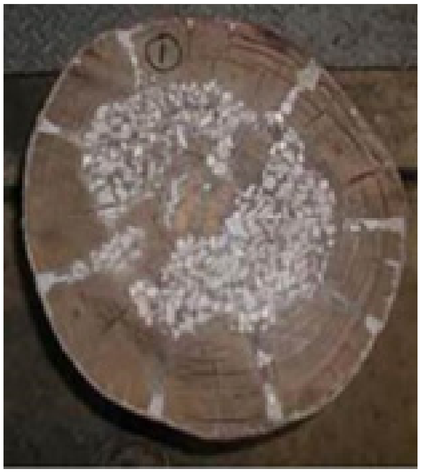


Figure 2-45 Timber pile impregnated with resin to fill voids

Figure 2-46 3FRP-wrapped timber piles

Figure 2-47 A timber pile that has failed due to buckling of the natural fibers under compressive loads

Figure 2-48 A timber pile similar to the one in Figure 247 failed at a much higher load due to confinement provided by the FRP wrap

Photos courtesy of Kim KH and B Andrawes, Load Rating and FRP Retrofitting of Bridge Abutment Timber Piles[23]

E14. Other

FRP composites enable designers to create new applications for transportation infrastructure, such as the utility box cover shown in Figure 2-49 and Figure 2-50. The "E14 Other" designation is set aside for applications not covered in the previous categories.

Figure 2-49 GFRP utility box cover in poor condition

Figure 2-50 Close up of deteriorated utility box cover

3 FRP for New Construction

FRP Uses

FRP composites have numerous traits that can be beneficial when used in components and systems for new construction. Corrosion resistance, high strength-to-weight ratio, and the ability to tailor its properties are some that a designer might find advantageous. When evaluating possible uses for FRP in infrastructure, it is important to remember that many design variations are possible for any application and future applications/ designs will likely be devised.

Table 31 lists the uses of FRP for new construction that have been identified. The identification numbers (1 through 22), proceeded by an N (for new), are assigned for ease of reference and tracking. The corresponding RI indicates the maturity level of each use, as described in Table 3-1. The values for RI presented below can be used as a tool for decision-making, with the recognition that they are only intended to be an approximation. The appropriateness of using each technology in any given situation is a matter of judgment on the part of the owner. The risk level of any decision is dependent on site conditions and many other factors.

Table 3-1 FRP uses and readiness index for new construction

FRP Use	RI*
N1. Concrete reinforcement (reinforcement, dowels)	1
N2. Concrete prestressing (pre-tensioning)	2
N3. Concrete prestressing (post-tensioning)	2
N4. Stay-in-place (SIP) concrete forms (decks, substructures)	2
N5. Superstructures – FRP beams and slabs	1
N6. Hybrid superstructure system – FRP beams and slabs	1
N7. Hybrid superstructure system – concrete-filled FRP tubes	1
N8. Hybrid superstructure system – FRP with glue-laminated lumber (glu-lam)	1
N9. Structural deck, FRP, or hybrid	1
N10. Pedestrian bridges	1
N11. Sidewalks	1
N12. Bridge drains and scuppers	1
N13. Load-bearing pile foundations, FRP or hybrid	4
N14. Marine fenders (piles, wales)	1
N15. Marine floats	2
N16. Sheet piling	2
N17. Noise barrier	3
N18. Wind fairing	3
N19. Railing – bridge, guide, and guard	4
N20. Culverts	3
N21. Light, sign, or signal structures	4
N22. Other	

*1 = Practice ready, 2 = Maturing, 3 = Under development, 4 = Emerging; Refer to Table 12 for descriptions of each RI.

The list is not intended to exclude any potential application, but is a list of the most common or contemplated uses. A brief introduction to each application is provided in the following sections.

N1. Concrete reinforcement (reinforcement, dowels)

Available Guidance

AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings[24]

440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars[25]

440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures[26]

Preventing Bridge Deck Corrosion Through Fiber-Reinforced Polymers[27]

Fiber-Reinforced Polymer (FRP) Reinforcing Bars and Strands[28]

Possible Suppliers		
Product	Supplier	Website
TUF-BAR™	BP Composites Ltd.	http://www.bpcomposites.com/products/tuf-bar/
XBar™	C1 Pultrusions LLC, an 80%-owned subsidiary of TecModo Industries Inc. (formerly CarbonOne Technologies Inc.)	http://www.tekmodo.com/construction/
WondeRebar	Composite Rebar Technologies	http://www.hollowrebar.com/
AslanFRP	Hughes Brothers, Inc.	http://www.aslanfrp.com/
C-Bar®	Marshall Composite Systems, LLC	http://www.marshallcomposite.com/
V-ROD	Pultrall Inc.	http://www.vrod.ca/
RocketRebar™	Raw Energy Materials Corp.	http://www.newrebar.com/
Information source: J. Busel, American Composite Manufacturers Association (ACMA)		

FRP reinforcement is of interest to states because rusting steel reinforcement has been the principal cause of deck deterioration for many decades. Bridge decks are exposed to water, freeze-thaw cycles, and often de-icing salts. Corroding steel expands and as the volume increases, cracks appear in the concrete surface. The penetration of water accentuates the problem because when temperatures drop below freezing, water

24 AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, First Edition, American Association of State Highway and Transportation Officials, 2009, https://bookstore.transportation.org/item_details.aspx?id=1545

25 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars, American Concrete Institute, 2015, https://www.concrete.org/store/productdetail.aspx?ItemID=440115

26 440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, American Concrete Institute, 2007, https://www.concrete.org/store/productdetail.aspx?ItemID=44007&Format=DOWNLOAD

27 Preventing Bridge Deck Corrosion Through Fiber-Reinforced Polymers, Brief No. 0092-05-02, Wisconsin Highway Research Program, Wisconsin Department of Transportation, August 2010, http://wisconsindot.gov/documents2/research/05-02-research-brief.pdf

28 Fiber-Reinforced Polymer (FRP) Reinforcing Bars and Strands, Structures Design – Transportation Innovation, Florida Department of Transportation, http://www.fdot.gov/structures/innovation/FRP.shtm

also expands. While carbon fiber is cost-prohibitive, GFRP is considered a cost-effective means of providing corrosion-resistant reinforcement. GFRP is manufactured by pultrusion. Manufacturers each have their own method for "deforming" the bars to achieve a good bond with the concrete matrix.

Oregon's Millport Slough Bridge can be used as a case study (see Figure 3-1 through Figure 3-3). In 2009, GFRP reinforcement was placed in a concrete deck. Oregon gives special attention to the protection of concrete reinforcement in coastal areas (i.e., within one air mile of the ocean) and areas subject to snow and ice. In this case, being near the Pacific Ocean, GFRP reinforcement was used for transverse and bottom longitudinal reinforcement. Stainless steel reinforcement was used for negative moment, deck overhang, and bridge rail curb reinforcement. Approximately $195,000 was saved using GFRP bars when compared to cost of stainless steel bars.

Figure 3-1 Aerial view of Millport Slough Bridge to illustrate its exposure to salt and moisture

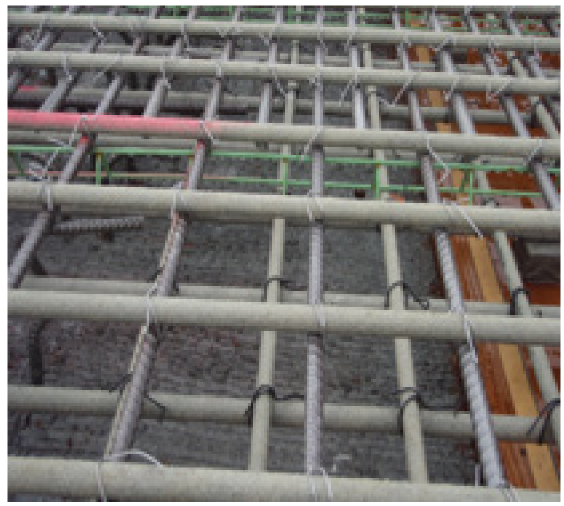


Figure 3-2 GFRP deck reinforcing used with stainless steel

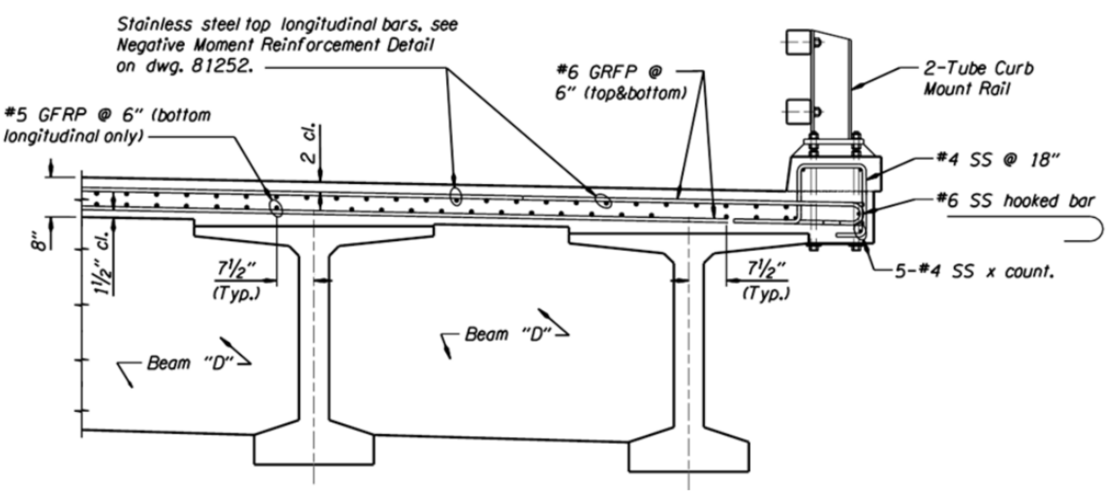


Figure 3-3 Deck section detailing reinforcement

Concrete safety shapes (e.g., Jersey barrier) are critical features on highways. GFRP has been used in successful full-scale tractor-trailer crash tests that demonstrate its suitability as an alternative to steel reinforcement, especially in corrosive environments. In April 2016, Ryerson University[29] and TEMCORP[30] jointly conducted a crash test in accordance with MASH[31] Test Level 5 (TL5) requirements at Texas A&M Transportation Institute[32]. The MASH TL5 crash test involves a 40-ton (36,000 kg) tractor-trailer impacting the barrier at a nominal speed of 50 miles per hour (80 kilometers per hour) at a 15º angle. The barrier wall was designed using GIII TemBar[33] 180° hooks and straight bars. A video is available online[34].

Even though GFRP is corrosion-resistant, sufficient concrete cover needs to be provided because of serviceability, constructability, and thermal compatibility considerations. Cracking can occur over bars if insufficient cover is provided.

GFRP has been used for temporary structures so that the reinforced concrete can be cut out when it is no longer needed.

Nonferrous reinforcement has also been used in situations when electromagnetic waves would cause a problem, such as infrastructure near electronic tolling facilities.

Table 3-2 provides typical ranges for properties of steel and pultruded GFRP to illustrate the differences. Note that the property values cannot be assumed to be the same in both directions for anisotropic materials like FRP. The properties of GFRP bar also varies according to manufacturer.

Extensive research has been and continues to be performed to evaluate the degradation mechanisms of reinforced concrete decks and to understand better the factors that determine service life.

Property	Units	Pultruded GFRP		Steel
Density	lb/ft^3	longitudinal	Transverse	ASTM A709 Grade 50
Tensile Strength	psi	30,000	7,000	490
Tensile Modulus	psi	2.8 x 10^6	1 x 10^6	30 x 10^6
Flexural Strength	psi	30,000	10,000	65,000
Flexural Modulus	psi	1.8 x 10^6	0,8 x 10^6	30 x 10^6
Coefficient of Thermal Conductivity	(BTU in. /hr ft^2 °F))	4		323
Coefficient of Thermal Expansion	in./in./°D	7 to 8 x 10^6		6 to 8 x 10^6

Table 3-2 A comparison of GFRP and steel properties

29 Ryerson University, Toronto, Ontario, Canada, http://www.ryerson.ca/

30 TEMCORP, Temcorp Industries Ltd., http://temcorp.ca/

31 Manual for Assessing Safety Hardware (MASH), Safety, Federal Highway Administration, U.S. Department of Transportation, http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/ctrmeasures/mash/

32 Texas A&M Transportation Institute, Texas A&M University System, https://tti.tamu.edu/

33 TemBar, Temcorp Industries Ltd., http://temcorp.ca/tembar/

34 Mostafa A, TemCorp Crash Test April 2016, Texas A&M Transportation Institute, https://www.youtube.com/watch?v=5QO0QjkF6rE

In summary, the use of GFRP concrete reinforcement is especially attractive when:

- Reinforced concrete is susceptible to corrosion by chloride ions or chemicals
- There is a need for reinforcement that is electromagnetically transparent, such as infrastructure near electronic tolling facilities
- Concrete is placed temporarily but will be removed by cutting through the section

N2. Concrete prestressing (pre-tensioning)

Available Guidance

Available Guidance

440.4R-04 Prestressing Concrete Structures with FRP Tendons[14]

When P/S strands are protected from conditions that allow corrosion, the component can last for 75 years or more. In some states where deicing salts are used in harsh climates, P/S beams are prone to deterioration due to corrosion. Box beams, for instance, have been known to collect and store water that has condensed inside the hollow section, degrading the steel P/S strands.

FRP made with carbon fiber does not corrode, is commercially available, and is suitable for P/S applications. Aramid fibers can also be used. As stated in the discussion of E7. Strengthening concrete with FRP post-tensioning, glass fiber is not appropriate for P/S because of it propensity to fail by creep rupture.

P/S concrete with FRP requires that the tendons have special anchorages to prevent damage to the fibers when gripping and tensioning them during fabrication. Usually, the special anchorage is spliced to a common steel strand to keep consistency with the precasters' typical stressing operations.

In coastal areas, CFRP P/S strands hold potential for greatly extending the service life of concrete piles by eliminating corrosion as a cause of deterioration. DOTs in Michigan, Florida, Maine, and Virginia have researched this application; Florida is implementing it in P/S concrete piles to have a product that can resist corrosion when exposed to a marine environment. NCHRP is in the process of developing guidance for design and construction of FRP stressing tendons (see Figure 3-4 through Figure 3-8.).

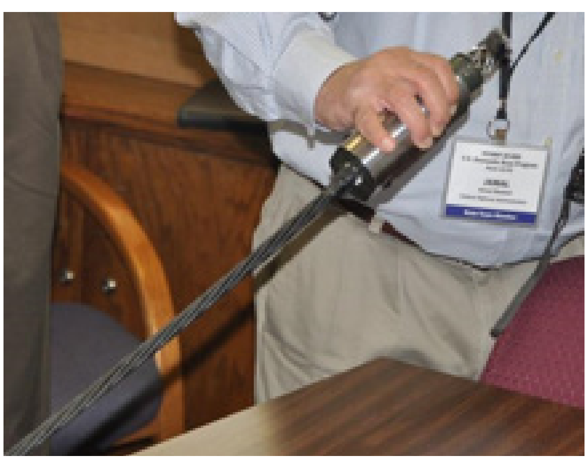


Figure 3-4 Carbon tendon used in P/S applications

Figure 3-5 Concrete pile P/S with CFRP

Photo courtesy of FDOT

Carbon fiber composite cable (CFCC) was used for an overpass bridge in Kittery, Maine. MDOT has used CFCC P/S strands in box beams on Route M102 over Plum Creek, Southfield, MI). Table 32 and Table 33 compare the material to steel, with which most civil engineers are familiar.

Property	Steel	CFRP (CFCC)
Strand diameter (in)	0.6	0.6
Effective strand area (in^2)	0.217	0.179
Modulus of elasticity (ksi)	28,500	22,480
Ultimate tensile strength, f_{pu} (KSI)	270	339

Table 3-3 CFCC properties compared to those of steel tendons

Design parameter	Steel	CFRP (CFCC)
Stress limit immediately prior to transfer (f_{pbt})	0.75 f_{pu}	0.65 f_{pu}
Initial pull force (kips)	44.0	35.5
Environmental factor	1.0	.90
Strength resistance factor	1.0	0.65 to 0.85

Table 3-4 CFCC design variables compared to those of steel

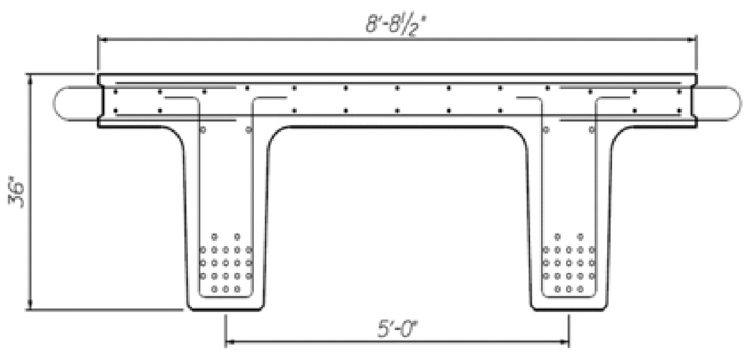


Figure 3-6 Cross-section with reinforcement details

Figure 3-7 Reinforcement and CFRP P/S strands

Figure 3-8 Completed bridge in Kittery, Maine, with carbon P/S

N3. Concrete prestressing (post-tensioning)

> ***Available Guidance***
>
> 440.4R-04 Prestressing Concrete Structures with FRP Tendons[14] Carbon Fiber Reinforced Polymer Prestressing[35] Carbon Fiber Post-Tensioned Cables Reduce Bridge Deck Cracking, Extend Service Life[36] Use of Unbonded CFCC for Transverse Post-Tensioning of Side-by-Side Box-Beam Bridges[37] Dr. Nabil Grace Publications[38]

Bridge beams are sometimes designed to be PT laterally to ensure good load distribution. While this is a different use from pretensioning, the materials and techniques are similar. PT can also be used to strengthen a member. As in the pretensioning application (N2. Concrete prestressing (pre-tensioning)), gripping and anchoring the tendons is a very important detail to address.

MDOT and Lawrence Technical University[39] are recognized as leaders in this area.

In 2012, MaineDOT used carbon tendons to PT Little Pond Bridge in Fryeburg (see Figure 3-9 and Figure 3-10.

N4. Stay-in-place (SIP) concrete forms (decks, substructures)

Figure 3-9 Hydraulic jacks apply stress to transverse CFRP PT strands

Figure 3-10 Final appearance of transverse PT strand

---

35 Chynoweth MJ, Carbon Fiber Reinforced Polymer Prestressing, AASHTO Innovations Initiative, AASHTO SCOBS Technical Committee T6 – FRP Composites, 2015, http://aii.transportation.org/Documents/CFRP/cfrp-scobs-annual-mtg-2015.pdf

36 Carbon fiber post-tensioned cables reduce bridge deck cracking, extend service life, Research Spotlight, September 2008, Michigan Department of Transportation, https://www.michigan.gov/documents/mdot/MDOT_Spotlight_CFCC_469162_7.pdf

37 Grace NF and E Jensen, et al., Use of Unbonded CFCC for Transverse Post-Tensioning of Side-by-Side Box-Beam Bridges, Lawrence Technological University, Michigan Department of Transportation, February 2008, https://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1509_Part_1_228939_7.pdf

38 Dr. Nabil Grace Publications, Lawrence Technological University, https://www.ltu.edu/nabil_grace/publications.asp

39 Lawrence Technological University, Southfield, Michigan, https://www.ltu.edu/

Since FRP is light, strong, and corrosion-resistant, it is attractive for SIP concrete formwork, especially in corrosive environments. For decks, these forms would be an alternative to galvanized corrugated steel forms. Figure 3-11 and Figure 3-12 illustrate a prefabricated system that combines an FRP grid reinforcement with FRP stay-in-place (SIP) forms for concrete.

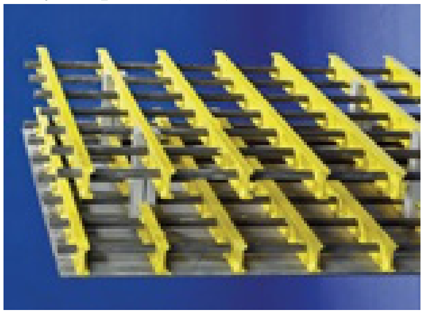


Figure 3-11 A proprietary SIP form with two integral mats of reinforcement

Figure 3-12 Concrete placement on the combined reinforcing/SIP form product shown in the previous figure.

Photos courtesy of Strongwell[40]

The lightweight GRIDFORM™[41] panel, which weighs only 4.7 pounds per square foot, is shop-fabricated in very large units that are limited only by shipping constraints to approximately 50 feet by 8 feet.

For columns and other parts of a bridge substructure, FRP can provide environmental protection as well as the other benefits. Concrete in splash zones with exposure to water and or salt spray could particularly benefit.

N5. Superstructures – FRP beams and slabs

GFRP has been used for corrosion-resistant beams and slabs and dozens have been installed in the U.S. and internationally (see Figure 3-13 and Figure 3-14). Deflection, rather than strength, controls the design because GFRP has a low modulus of elasticity. This results in a high factor of safety, which provides a conservative but less cost-competitive design. Although the structural performance of these structures under static load has been good, the durability of some that have been placed in service has failed to live up to expectations, leading to their removal from service. They may have had poor design details or possibly inadequate QA/QC measures during manufacture.

N6. Hybrid superstructure system – FRP beams and slabs

Hybrid systems were developed to optimize cost and overall performance. Unlike FRP beams and slabs,

Figure 3-13 Corrosion-resistant FRP beams (double web)

Figure 3-14 A movable bridge fabricated of FRP

Photos courtesy of Strongwell[42]

40 Structural Reinforcements, Strongwell Corporation, http://strongwell.com/products/structural-reinforcements/

41 GRIDFORM™ FRP Bridge Deck System, Strongwell Corporation, https://www.strongwell.com/wp-content/uploads/2013/04/GRIDFORM-Flyer.pdf

42 Bridge Components, Strongwell Corporation, http://www.strongwell.com/products/bridge-components/

which are made entirely of FRP material, hybrids usually pair FRP with another composite material,

> ***Available Guidance***
>
> NCHRP Report 564, Field Inspection of In-Service FRP Bridge Decks[43]

concrete, to create a more efficient system. They benefit from concrete's high compressive strength and FRP's tensile strength. Despite the more efficient use of material, the design of hybrid systems is still governed by serviceability (i.e., deflection limits) rather than strength. See N5. Superstructures – FRP beams and slabs.

In 2004, Erie County, New York, installed four FRP-concrete hybrid slabs, each weighing 115 pounds per square foot, as part of an accelerated bridge construction project on New Oregon Road (see Figure 3-15 and Figure 3-16). Demolition, construction of modular abutments, superstructure installation, railing, and approaches were completed in 31 days. Inventory ratings for the bridge are Inventory HS96 (173 tons) and Operating HS148 (267 tons). The high capacity is testament to the design of FRP structures being deflection-driven. The maximum live load deflection under HS25 design load has been determined to be L / 1745. Dead-load stresses are less than 4% of the FRP's ultimate value, which will eliminate any potential for creep for the short-span superstructure (31 feet).

One type of hybrid composite beam was developed using seed money from the Transportation Research Board's (TRB's) IDEA Programs[44]. The beam consists of a self-consolidating concrete arch inside of a rectangular FRP shell, with tension

Figure 3-15 FRP/concrete hybrid panels (two of four required for the New Oregon Road bridge)

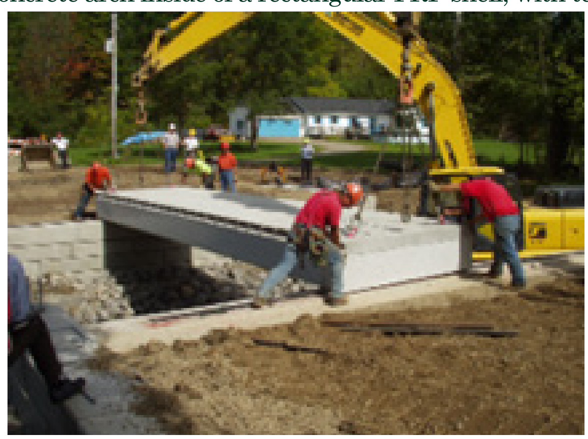


Figure 3-16 Placement of a prefabricated hybrid panel (see Fig 3-15)

loads carried by steel strands or glass fiber infused in the bottom of the box. This type of structural member exploits the advantages of concrete, steel, and composites to form a cost effective beam that is lighter, stronger, and expected to be more durable than conventional concrete or steel beams. The design uses a typical concrete deck.

Figure 3-17 shows High Road Bridge in Lockport Township, Illinois. Each of the six hybrid composite beams measures 3'6" high x 2' wide x 57' long. Figure 3-18 shows a similar structure in Missouri.

Table 3-5 lists completed projects of this type.

43 NCHRP Report 564, Field Inspection of In-Service FRP Bridge Decks, The National Academies of Sciences, Engineering, and Medicine, 2006, http://www.trb.org/Publications/Blurbs/156715.aspx

44 TRB's IDEAS Programs, Innovations Deserving Exploratory Analysis, Transportation Research Board, The National Academies of Sciences, Engineering, and Medicine, http://www.trb.org/IDEAProgram/IDEAProgram.aspx

The video[45] at Composites Today is of a hybrid structure designed and built in Poland.

Figure 3-17 High Road over Long Run Creek in Illinois

Photos courtesy of HCB Inc.[46]

Figure 3-18 Route 49 over Ottery Creek Overflow in Missouri

Table 3-5 Projects with hybrid composite beams developed under TRB's IDEA Programs

Location	Year Built	Characteristics
Illinois		
High Road / Long Run Creek	2008	1 span, 6 beams, L = 58′, w = 42′
Kentucky		
Bridge 4, Fort Knox, U.S. Army Corps of Engineers	2012	1 span, 5 beams, L = 40′, w = 27′
Maine		
Knickerbocker Bridge, Boothbay Harbor	2010	8 spans, 8 beams, L = 540′, w = 32′
Downeast Institute Pier, Beals Island	2010	3 spans, 4 box beams, L = 99′, w = 30′
Maryland		
Potomac Hollow	2014	1 span, 6 beams per span, L = 30′, w = 25′
Missouri		
Rte 49 BO478 / Ottery Creek Overflow	2011	2 spans, 6 beams, L = 101′, w = 26′
Rte 76 / Beaver Creek Bridge BO439	2010	3 spans, 5 beams, L = 178′, w = 26′
Sons Creek Bridge BO410	2011	1 span, 3 box beams, L = 106′, w = 30′
New Jersey		
Rte 23 over Peckmans Brook, Cedar Grove	2009	1 span, 6 beams, L = 32′, w = 66′
Virginia		
Rte 205 / Tide Mill Stream, Colonial Beach	2012	1 span, 8 beams, L = 48′, w = 32′
West Virginia		
Rte 60/29 / Campbell's Creek Dry Branch	2013	1 span, 3 beams, L = 106′, w = 24′

Sources:
Keeping Our Bridges Safe: 2014 Report[47]
Advanced Infrastructure Technologies[48]
IBRD Program[49]

45 Com-bridge: Construction of a Bridge Made of FRP Composites, Composites Today, Composites Media Ltd., http://www.compositestoday.com/2016/08/first-polish-road-bridge-made-using-frp-composites/?utm_content=buffer8f56e&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer

46 Hillman Composite Beams (HCB®), HCB Inc., http://www.hcbridge.com/

47 Keeping Our Bridges Safe: 2014 Report, Maine Department of Transportation, http://www.maine.gov/mdot/pdf/kobs2014.pdf

48 Advanced Infrastructure Technologies, http://www.aitbridges.com/

49 Innovative Bridge Research and Deployment (IBRD) Program, 2012 Discretionary Grant Program Fact Sheets, Special Federal-aid Funding, Federal Highway Administration, U.S. Department of Transportation, http://www.fhwa.dot.gov/discretionary/2012ibrd.cfm

N7. Hybrid superstructure system – concrete-filled FRP tubes

Concrete-filled CFRP tube arches is a particular hybrid design that AASHTO has embraced with the publication of guidelines for their design and construction. These are buried structures most appropriate where vertical clearance or the waterway opening is not a concern. See Figure 3-19 through Figure 3-21. Table 3-6 summarizes installations of this type of bridge.

Figure 3-19 An underpass for recreational vehicles constructed with concrete-filled FRP tubes

Hybrid composite arches were developed at the University of Maine for rapid installation and longevity. The buried arches are primary structural members comprising lightweight composite tubes filled with concrete. The arches can be supported on rock, piles, or concrete footings. FRP corrugated sheeting spans between the individual tubes to allow for backfill. This system is typically used within a span range of 25 to 70 feet. The construction specifications used for these structures are readily available.

Figure 3-20 FRP tube arches erected

Figure 3-21 The completed arch structure

Table 3-6 Projects that have used concrete-filled FRP tube arches

Location	Year Built	Characteristics
Connecticut		
Weston	~2013	Route 57 over West Branch Saugatuck River
Maine		
B&A Overhead Bridge, Lagrange (Owner: MaineDOT)	2013	36′1″ span, 58′ width, 56° skew, staged construction, 13 each 12″ GFRP tubes spaced at 5' c.c.
Ellsworth	2013	34′4″span, 11 arches
Farm Access Underpass, Caribou (Owner: MaineDOT)	2011	54′2″ span, 55′ width, 30° skew, 22 each 15″ CFRP tubes at 2′8″ c.c.
Jenkins Bridge, Bradley	2010	28′6″ span, 14 arches
McGee Bridge, Anson	2009	28′ span, 9 arches
Neal Bridge, Pittsfield	2008	29′span, 23 arches
Perkins Bridge, Belfast Owner: MaineDOT	2010	47′7″ span, 45′ width, 0° skew, 16 each 15″ CFRP tubes at 2′11″ c.c.
Royal River Bridge, Auburn	2010	38′ span, 13 arches
Tom Frost Memorial Snowmobile/Pedestrian Bridge, Hermon	2010	44′6″ span, 3 arches
Tide Mill 2 Bridge, Edmunds Township (design/build)	2015	56′ span, 13 tubes @ 4′-2 ½″, composite decking
Massachusetts		
Fitchburg	2011	37'6" span, 15 arches
Michigan		
Harbor Beach	2012	37′6″ span, 16 arches
Sunfield Township	2013	37′8″ span, 24 arches
New Hampshire		
Pinkham's Grant	2011	24′6″ span, 6 arches
Rhode Island		
Browning Mill Bridge	2012	Arcadia Road over Roaring Brook

Sources:

Keeping Our Bridges Safe: 2014 Report[50]

Advanced Infrastructure Technologies[51]

Innovative Bridge Research and Deployment (IBRD) Program[49]

50 Keeping Our Bridges Safe: 2014 Report, Maine Department of Transportation, http://www.maine.gov/mdot/pdf/kobs2014.pdf

51 Advanced Infrastructure Technologies, http://www.aitbridges.com/

N8. Hybrid superstructure system – FRP with glue-laminated lumber (glu-lam)

Available Guidance

FRP Bridge Decks[52]

How Have Composite Bridges Measured Up?[53]

In-Service Performance Monitoring of a CFRP Reinforced HPC Bridge Deck[54]

The inclusion of even thin CFRP laminates has been shown to enhance dramatically the structural performance of glu-lam timber. While timber is not the primary material for structures in the US, it is popular in certain areas because of historical use, availability and aesthetics. See Figure 3-22 through Figure 3-24.

Figure 3-22 Glu-lam beam with FRP plate bonded to the bottom

Photo courtesy of Hosteng TK, et al.[55]

Figure 3-23 Glu-lam beam with FRP integrated into the laminations

Photo courtesy of Gentry TR[56]

Figure 3-24 Deep glu-lam beams containing FRP laminates

52 Craig FP and T Sweet, Session 1.4: FRP Bridge Decks, Eleventh Statewide Conference on Local Bridges, C&S Engineers, Inc., and Lewis County (New York) Highway, New York State Department of Transportation https://www.dot.ny.gov/divisions/engineering/structures/repository/events-news/presentations-04/1-4_frp_deck.pdf

53 Black S, How have composite bridges measured up?, Composites World, January 8, 2016, http://www.compositesworld.com/blog/post/how-have-composite-bridges-measured-up

54 In-Service Performance Monitoring of a CFRP Reinforced HPC Bridge Deck, New Hampshire DOT Research Record, New Hampshire Department of Transportation, August 2010, https://www.nh.gov/dot/org/projectdevelopment/materials/research/projects/documents/FHWA-NH-RD-14282I.pdf

55 Hosteng TK, et al., Evaluation of a Timber Bridge for the Secondary Road System Using FRP Reinforced Glued-Laminated Girders, Proceedings of the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2007, http://www.ctre.iastate.edu/pubs/midcon2007/HostengTimber.pdf

56 Gentry TR, Performance of Glued-Laminated Timbers with FRP Shear and Flexural Reinforcement (prepublication text); published in Journal of Composites for Construction, 15:5; October 2011, American Society of Civil Engineers, http://squall.coa.gatech.edu/sites/default/files/filesfiles/gentry%20jcc%20frp%20glulam.pdf

N9. Structural deck, FRP, or hybrid

Nationwide, a large amount of deck area is considered deficient. Because of its inherent corrosion-resistance, FRP can be used to mitigate the environmentally unsustainable practice of replacing a bridge deck once or twice over the life of the bridge. Table 3-7 lists FRP decks that are in service. The list is provided as an indication of deck use to date; however, it has not been verified recently, so caution is advised with its use. Florida, Missouri, Ohio, and West Virginia have taken decks out of service because of durability issues. FRP decks are illustrated in Figure 3-25 through Figure 3-29.

Table 3-7 FRP decks in service

State	County	Town or City	Description	Supplier	Year	SF	IBRC# or Funding
DE	New Castle	Wilmington	Old Milltown Road / Mill Creek	HC	1999	663	N
IA	Scott	Bettendorf	53rd Ave. Crow Creek	MMC	2001	4,604	IA-98-01
IA	Winneshiek	Jackson	Iowa 24 / Goddard Creek		2004	540	IA-03-03
IL	Morgan	Jacksonville	S.Fayette St. / Town Brook	MMC	2001	2,189	IL-98-08
KS	Crawford	Pittsburg	SR126	KSCI	1999	1,440	N
KS	Crawford	Pittsburg	SR126	KSCI	1999	1,440	N
KS	Kansas City	Kansas City	truss / Kansas River	KSCI	2005		
LA	Assumption		Pierre Part Bayou	Alcan	2009		IBRD
MD	Cecil		Wheatly Road	HC	2000	816	
MD	Harford	Rocks Park	MD24 / Deer Creek	MMC	2001	3,944	MD-00-01
MD	Frederick		Blacks Mill Road / Little Hunting	Str?	2003	840	MD-03-02
MO	Phelps	St. James	St. John's Street Bridge	KSCI	2000	612	
MO	Phelps	St. James	Jay Street Bridge	KSCI	2000	612	
NC	Durham	Oak Grove	SR1814 / Little Lick Creek	MMC	2001		NC-01-01
NY	Chemung	Wellsburg	NY367 Bentley Creek	HC	1999	3,360	N
NY	Chemung	Swartwood	NY223 / Cayuta Creek	HC	2000	3,741	N
NY	Allegany	Wellsville	S. Broad St. / Dyke Creek	HC	2000	2,876	NY-98-02
NY	Warren	Warrensburg	NY418 / Schroon River	MMC	2000	4,060	NY-98-07
NY	Lewis		CR46 Osceola Road / E Branch	MMC	2001	935	NY-01-08
NY	Washington		CR153 / White Creek	HC	2002	1,474	NY-01-03
NY	Lewis		Erie Canal Road / Independence	MMC	2003	2,420	NY-01-05
NY	Lewis		CR32 Glendale Road / Roaring			2,079	NY-03-03
OH	Greene	Xenia	Ohio-Erie Trail / Shawnee Creek	CP	1997	294	
OH	Darke	Ansonia	SR47 / Woodington Run	MMC	1999	2,208	DARPA
OH	Knox		CR114 / Eliot Run	HC	2000	975	Project 100
OH	Hamilton		Five Mile Road Bridge #0171	HC	2000	1,232	Project 100
OH	Clark		Sintz Road / Rock Run	HC	2000	1,860	Project 100
OH	Knox		Sycamore Road	HC	2000	975	
OH	Delaware		CR175 Tyler Road / Bokes Creek	FRS	2001	2,147	Y
OH	Franklin	Columbus	Stelzer Road	FRS	2001	13,545	
OH	Hamilton		Five Mile Road Bridge #0071	HC	2001	1,290	Project 100

State	County	Town or City	Description	Supplier	Year		SF	IBRC# or Funding
OH	Hamilton		Five Mile Road Bridge #0087	HC	2001		1,410	Project 100
OH	Hamilton	Anderson	Eight Mile Rd	ComAdv	2008		22'	IBRD
OH	Ashtabula		Shaffer Road	HC	2001		2,975	Project 100
OH	Montgomery	Kettering	Spaulding Road	HC	2001		4,648	Project 100
OH	Dayton	Wright	Hebble Creek	WC	2001		544	Project 100
OH	Washington		CR76 / Cat's Creek	MMC	2002		1,920	C4I
OH	Greene		Fairgrounds Road / Little Miami	MMC	2002		7,074	C4I
OH	Montgomery		SR49 Pleasant Plain Road / Great	BPI	2003		411	OH-98-05
OH	Geauga		Hotchkiss Road / Cuyahoga River	MMC	2003		1,792	C4I
OH	Defiance		County Line Road / Tiffin River	MMC	2003		5,096	C4I
OH	Clinton		Hales Branch Road / West Fork of	MMC	2004		1,572	C4I
OH	Summit		Hudson Road / Wolf Creek	MMC	2004		3,939	C4I
OR	Clatsop	Astoria	Rte 105 Lewis & Clark Bridge	MMC	2001		2,331	OR-00-0
OR	Clatsop		Rte 105 Old Young's Bay Bascule	MMC	2002		3,275	OR-00-01
OR	Mulnomah	Portland	Broadway / Williamette River	MMC	2004		11,970	OR-03-01
PA			Rowser Farm	CP	1998			
PA	Somerset		Rte 4003 / Laural Run	CP	1998		561	
PA	Chester	Valley Forge	Wilson Road / Valley Creek	HC	1998		1,063	N
PA	Butler	Boyers,	SR4012 / Slippery Rock Creek	MMC	2001		1,071	PA-01-02
PA	Bedford	Clair	TR565 / Dunning Creek	MMC	2002		1,991	PA-00-01
PA	Lycoming	English	T776 English Run	W	2009		896	PA-
SC	Spartanburg		Greenwood Road S42-655 / N-S	MMC	2001		2,156	SC-01-01
VA	Alleghany	Covington	Hawthorne Street / CSX RR	Str	2003		1,650	VA-03-01
VA	Tangier		Canton Road over Canton Creek	Zell	2006			VA-05
VT	Washington		Moretown Bridge Lovers Lane /				1,264	VT-03-01
WA	Douglas		Chief Joseph Dam Br Pearl Hill	MMC	2003		9,907	WA-01-01
WA	Snohomish		Granite Falls Bridge #102 / S Fork		2004		9,240	WA-03-01
WV	Lewis		CR26/6 Laural Lick	CD	1997		322	N
WV	Taylor	Grafton	CR26 / Wickwire Run	CP	1997		682	N
WV	Ohio Co.	Wheeling	Market Street Bridge	CP	2001		10,080	WV-98-02
WV	Marion	Bridgeport	Katy Truss Bridge WV250 / 11	CP	2001		1,260	WV-98-07
WV	Raleigh	Princeton	Boy Scout Camp Bridge	HC	2001		806	
WV	Randolph	Elkins	Montrose Bridge	HC	2001		1,092	
WV	Pendleton	Hanover	SR23 Hanover / S. Branch of	KSCI	2001		3,164	WV-98-05
WV	Monroe	Peterstown	CR12/5 LaChein	BPI	2002		960	NA
WV	Cabell		Howell's Mill Bridge CR1 / Mud	MMC	2003		7,832	WV-01-01
WV	Monroe	Peterstown	Kite Creek	BPI	2003		768	NA
WV	Jackson		CR21/6 at Goat Farm	BPI	2004		600	

Figure 3-25 FRP on the Broadway Bridge in Portland, Oregon

Figure 3-26 FRP on the Morrison Bridge in Portland, Oregon

Figure 3-27 Deteriorated and repaired riding surface on the Morrison Bridge

Photo courtesy of Multnomah County Public Works Programs[57]

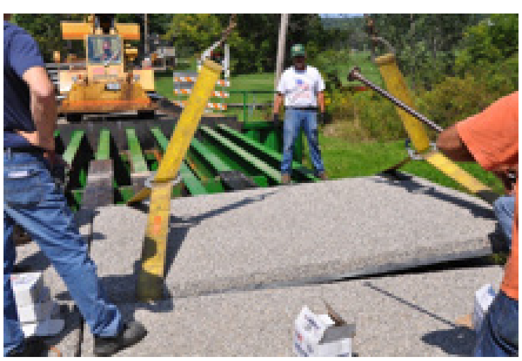


Figure 3-28 FRP deck panels with integral wearing surface

Figure 3-29 FRP deck topped with polymer concrete, subjected to heavy coal trucks

[57] Public Works Programs, Multnomah County, State of Oregon, https://multco.us/purchasing/public-works

Although the following excerpt is from a 10-year-old report, the conclusions of this Navy study[58] are still fairly accurate.

> *FRP composite deck systems have been studied in recent years to verify and validate the benefits of composite materials for this application. However, several issues are still being debated and researched, including:*
>
> - *Deflection/design criteria*
> - *Long-term performance*
> - *Extreme temperature behavior*
> - *Connections*
> - *Overlays*
> - *Specifications*
> - *Higher initial costs – up to two to three times that of conventional decks*
> - *Manufacturing methods*

N10. Pedestrian bridges

The use of FRP for foot bridges has gained momentum with the availability of AASHTO guidelines for truss structures[59] (see Figure 3-30). Because of their light weight and the ability to assemble them on-site, they are especially well suited to remote locations where it is impractical or undesirable to bring in large equipment that would destroy the natural environment. The U.S. Forest Service has employed them repeatedly (see Figure 3-31 for a completed FRP pedestrian bridge) and has published a report[60].

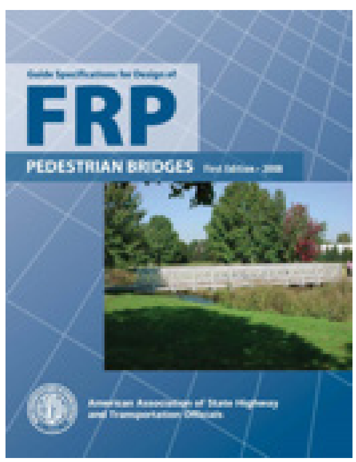


Figure 3-30 AASHTO Guide Specifications for FRP pedestrian bridges

58 Hoffard TA and LJ Malvar, Technical Memorandum TM-2384-SHR: Fiber-Reinforced Polymer Composites in Bridges: A State-of-the-Art Report, Naval Facilities Engineering Command, May 2005, http://www.dtic.mil/dtic/tr/fulltext/u2/a526493.pdf

59 Guide Specifications for Design of FRP Pedestrian Bridges, 1st Edition, 2008, American Association of State Highway and Transportation Officials, https://bookstore.transportation.org/item_details.aspx?id=1218

60 A Guide to Fiber-Reinforced Polymer Trail Bridges, U.S. Forest Service, U.S. Department of Agriculture, http://www.fs.fed.us/eng/pubs/pdfpubs/pdf06232824/pdf06232824dpi72.pdf

Figure 3-31 A typical FRP trail bridge, easily transported and assembled in remote locations

(Photo courtesy of U.S. Forest Service[61])

N11. Sidewalks

Sidewalks and bikeways are increasingly important due to an emphasis on multimodal transportation and recreational use of bridges. The high strength-to-weight ratio of FRP walkways makes it possible to incorporate these on both new and existing bridges, sometimes even cantilevered walkways. Additionally, the solid surface gives added protection to any supporting steel elements (see Figure 3-32 and Figure 3-33).

Figure 3-32 Installation of a lightweight sidewalk panel

Photo courtesy of Composite Advantage[62]

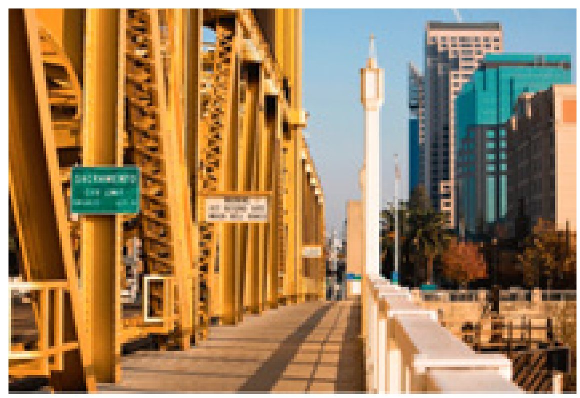


Figure 3-33 Cantilevered sidewalk on an existing truss

N12. Bridge drains and scuppers

Available Guidance

Fiberglass Bridge Downspouts[63]

FRP Bridge Drain Pipe[64]

Custom Fiberglass Manufacturing[65]

---

61 U.S. Forest Service, U.S. Department of Agriculture, http://www.fs.fed.us/

62 FRP Cantilever Sidewalks, Composite Advantage, http://www.compositeadvantage.com/products/cantilevered-sidewalks

63 Fiberglass Bridge Downspouts, Design Plastic Systems, Inc., http://www.designplasticsystems.com/products/grace-composites/fiberglass-bridge-downspouts

64 FRP Bridge Drain Pipe, Westfall Company, Inc., http://bridgedrainpipe.com/

65 Custom Fiberglass Manufacturing, Kenway Corporation, http://kenway.com/

Closed drainage systems are intended to transport rainwater from the traveled way to a place where it can be safely discharged. Pipes protect vulnerable bridge elements from the runoff, which can be chloride-contaminated; however, this subjects the pipes to extremely harsh conditions. FRP drains do not rust; yet, sized properly, they can withstand tensile stresses from the occasionally freezing of water within. Several states use FRP drains exclusively because of their good durability. See Figure 3-34 through Figure 3-39.

Figure 3-34 Fabrication of a drainage pipe by filament winding

Sikorsky Memorial Bridge, Connecticut, 2,470 linear feet of 12″ diameter pipe, 20 scuppers, 120 fittings, 10″ diameter drain pipe

Photo courtesy of Westfall Company, Inc.[66]

Figure 3-35 Fabrication of an FRP pipe and scupper

Photo courtesy of Westfall Company, Inc.

Figure 3-36 Combined FRP scupper and drain pipe

Figure 3-37 A rusted through steel pipe illustrates the primary benefit of FRP drains

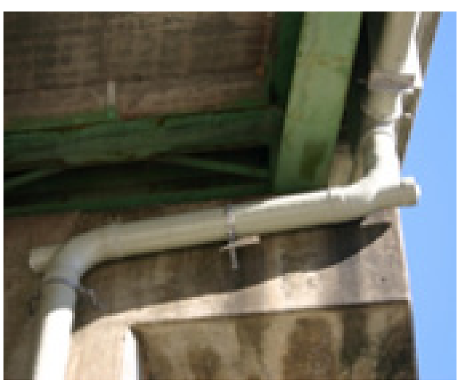


Figure 3-38 An FRP drain system in Oregon

Figure 3-39 FRP pipes being evaluated against steel

Photo courtesy of Kenway Corporation[67]

66 FRP Bridge Drain Pipe, Westfall Company, Inc., http://bridgedrainpipe.com/

67 Custom Fiberglass Manufacturing, Kenway Corporation, http://kenway.com/

Maine and Missouri are just two examples of DOTs that have discovered a niche use for FRP. Drain pipes made of composite materials can perform better than steel because they are immune to road salt and treatment chemicals that contaminate runoff water. While plastic pipe, such as PVC (polyvinyl chloride), has the same advantage, the fiber and resin in composite material makes FRP much stronger than plastic pipe, allowing FRP pipe to withstand repeated freeze/thaw cycles without damage. Being very lightweight, FRP drains are also easier to install than steel pipes of comparable strength.

FRP piping is readily available in various colors and diameters, so specifying it in contracts presents no unusual problems. Sections and fittings are usually fabricated for installation with adhesive socketed joints. MoDOT routinely uses composite drainage systems. Maine first deployed them in 2002 and continues to evaluate them for their ability to withstand ice build-up and a harsh marine environment. The long history of performance is an indicator that this is a practice-ready application (RI = 1).

Some major bridges have incorporated FRP drains:

- Pulaski Skyway, New Jersey, 35,000 linear feet
- Ben Franklin Bridge, Philadelphia, Pennsylvania, custom color
- Chicago Skyway, 15,000 linear feet, installed by two workers in a lift
- Huey P. Long Bridge over the Mississippi west of New Orleans, Louisiana
- Joe Montana Skyway south of Pittsburgh, Pennsylvania
- Peace Bridge between Ontario, Canada, and Buffalo, New York

N13. Load-bearing pile foundations, FRP or hybrid

FRP load-bearing piles are not commonly used, but initial trials conducted in Maine (see Figure 3-40) and Florida indicate that additional research would be beneficial. Hybrid piles (i.e., concrete with CFRP) would likely incorporate CFRP P/S tendons as described above in N2. Concrete prestressing (pre-tensioning).

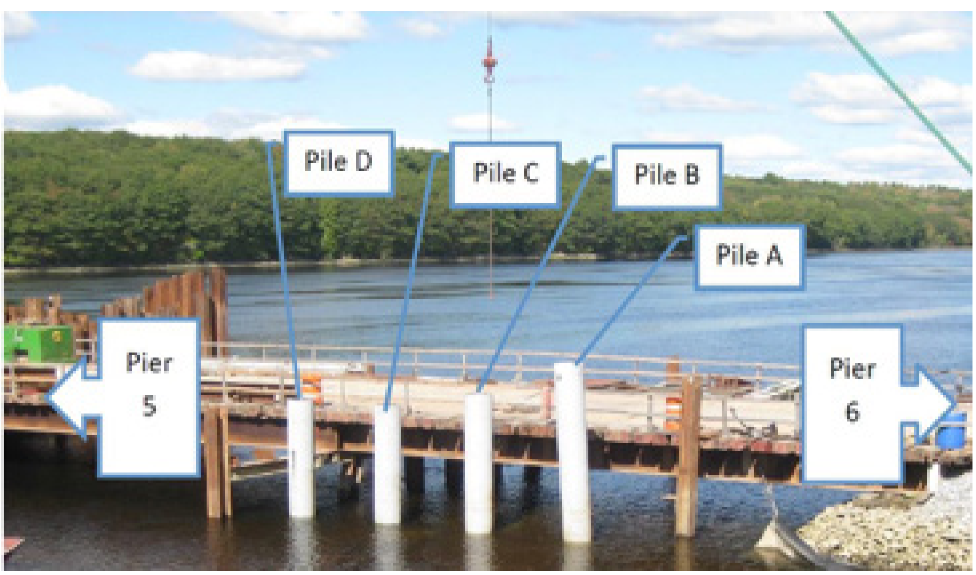


Figure 3-40 Pile configuration for FRP piles driven as part of a test program undertaken in Maine.

FHWA has produced a report entitled Behavior of Fiber-Reinforced Polymer Composite Piles Under Vertical Loads.[53]

N14. Marine fenders (piles, wales)

Fendering systems primarily resist lateral loads from barges and cargo ships that are docking. In this situation, the flexibility of FRP is considered an asset because it prevents damage and absorbs impact energy. The long-term durability of FRP in saltwater provides a significant advantage to FRP over traditional timber piles and horizontal wales made of wood. FRP fendering systems have been used successfully very extensively (see Figure 3-41 through Figure 3-43).

Figure 3-41 Fender piles absorb energy from lateral loads without damage

Photo courtesy of Federal Highway Administration[69]

Figure 3-42 Wales fabricated with GFRP bars encased in resins

Figure 3-43 Plastic fender systems reinforced with GFRP bars

Photo courtesy of Maine DOT

N15. Marine floats

Various entities in Maine have used FRP to make marine floats, docks, and even a floating bridge to take advantage of FRP's long-term durability in a coastal environment. Some examples follow.

FRP was used to replace an existing floating bridge in Sunset Lake, Brookfield, Vermont (see Figure 3-44). End-to-end, the 10 foam-filled pontoons totaled 500 feet.

68 Behavior of Fiber-Reinforced Polymer Composite Piles Under Vertical Loads, Federal Highway Administration, U.S. Department of Transportation, August 2006, https://www.fhwa.dot.gov/publications/research/infrastructure/geotechnical/04107/04107.pdf

69 Underwater Bridge Repair, Rehabilitation, and Countermeasures, Federal Highway Administration, U.S. Department of Transportation, April 2010, http://www.fhwa.dot.gov/bridge/nbis/pubs/nhi10029.pdf

Figure 3-44 Floating bridge in Vermont

MaineDOT pioneered FRP's use as an alternative to timber floats used in ferry service to the coastal islands (see Figure 3-45). Timber floats that are customarily used are very heavy and rot out quickly, so they are difficult to maintain. At Isle au Haut Ferry Landing, composite materials provided a solution that was one-third the weight of wood, virtually maintenance-free, and able to carry greater loads.

Figure 3-45 FRP floating docks, called floats, outperform timber.

Composites were used to build a fireboat pier in Jacksonville, Florida (see Figure 3-46). It is designed to remain functional in a Category 3 hurricane with winds of 110 to 130 miles per hour.

Figure 3-46 An FRP fireboat pier in Florida

A harbor camel provides setback for docking ships to protect both the ship and dock (see Figure 3-47 and Figure 3-48).

Figure 3-47 An FRP harbor camel

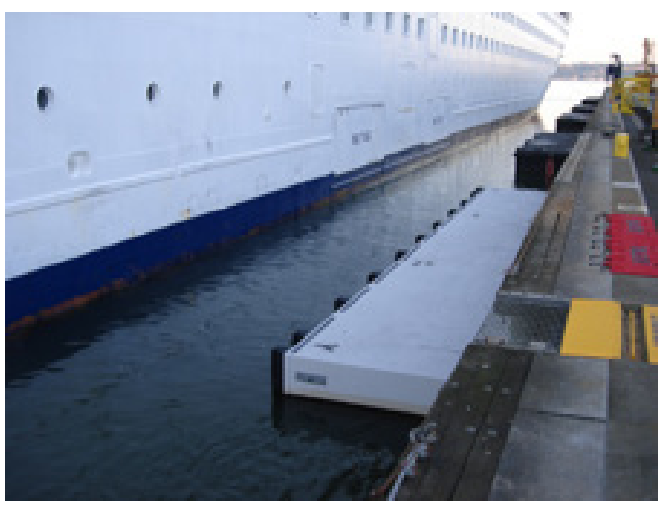


Figure 3-48 Composite stand-off harbor camel

N16. Sheet piling

Available Guidance

CMI Sheet Piling[70]

Sheet Piling and Round Pile[71]

SuperLoc™ Sheet Pile System Technical Information for Engineers[72]

FRP is produced as sheeting similar to steel sheet piling (Figure 3-49 and Figure 3-50). A DOT's use of sheeting may be predominately temporary, such as for excavations on a construction project, so the noncorrosive and lightweight nature of FRP may not offset the benefits of steel. FRP sheeting may be viable, depending on project-specific conditions and where permanent installations are needed. Although these products are available, they have not seen extensive use in the transportation infrastructure.

Figure 349 FRP sheeting is damage and corrosion resistant

Photos courtesy of Strongwell[73]

Figure 350 FRP sheet piling

N17. Noise barrier

FRP noise barriers have not received a lot of R&D, but their use has several important benefits. Being lightweight, they are relatively easy to install and impose little additional dead load to a structure, making the option attractive in retrofit situations. GFRP reinforcement could also be utilized in reinforced concrete noise barriers to utilize thinner concrete panels due to the reduced cover requirements and low service loads, which otherwise often controls the GFRP reinforcing design.

N18. Wind fairing

FRP is a versatile material that can be tailored for unique solutions. In 2004, New York's MTA Bridges & Tunnels/Triborough Bridge and Tunnel Authority and their consultant, Weidlinger Associates, devised an FRP use that would improve the aerodynamic characteristics of the Bronx-Whitestone Suspension Bridge's 2,300-foot main span, which was built in 1939 (see Figure 3-51 and Figure 3-52). A more streamlined deck and fascia reduces the possibility of vibration and flutter, contributing factors to the demise of the infamous Tacoma Narrows suspension bridge that collapsed in the 1940s. The design of the two bridges was very

70 CMI Sheet Piling, Crane Materials International, a Crane Group Company, http://cmisheetpiling.com/

71 Sheet Piling and Round Pile, Strongwell Corporation, http://www.strongwell.com/products/sheet-piling-round-pile/

72 SuperLoc™ Sheet Pile System: Technical Information for Engineers, Creative Pultrusions, Inc., http://www.creativepultrusions.com/index.cfm/fiberglass-pultruded-systems/composite-sheet-pile-system/engineering-technical-data-sheet/

73 Strongwell Corporation, http://www.strongwell.com/

similar. After the failure of the Tacoma Narrows Bridge, 24-foot-deep steel trusses were added to the Bronx-Whitestone Bridge to stiffen it, reducing the structure's response to high winds. Though unsightly, the 1946 retrofit allowed New Yorkers to use the bridge safely for over 50 years.

Figure 3-51 The aerodynamic characteristics of the Bronx-Whitestone Bridge were improved with the addition of FRP wind fairings.

Photo courtesy of Weidlinger Associates[74]

Figure 3-52 The wedge shaped wind fairing used on the Bronx-Whitestone Bridge, which is a twin of the ill-fated Tacoma-Narrows Bridge.

Photo courtesy of Weidlinger Associates[74]

Over time, however, the additional dead load became an issue, so a lightweight FRP wind fairing was designed and installed. After detailed analysis, the fairing was installed and the much heavier steel trusses removed, which reduced dead load in the main cables. MTA's engineers tested various fairing shapes to arrive at optimal effectiveness, cost, and appearance.

[74] Thornton Thomasetti, http://www.thorntontomasetti.com/

Some noteworthy project facts:

- 370 lightweight V-shaped FRP fairings were installed
- The fairings will stabilize the bridge in winds up to 120 miles per hour.
- Stability is ensured for a more than 100,000-year return period.
- The bridge's original sleek profile was restored.
- Over one million pounds of FRP was used, making it one of the largest uses of FRP in civil construction.

N19. Railing – bridge, guide, and guard

Safety railing made with just FRP is a use that presents a higher risk because it is such an important part of ensuring the public's safety. Despite the potential payoff, it is probably for this reason that there has been little research in developing an FRP rail.

> **Note:** The use of GFRP reinforcement in concrete barrier would be included in N1. Concrete reinforcement (reinforcement, dowels). Some testing has been done in the U.S. and Canada.

N20. Culverts

Drainage structures that span less than 20 feet are considered culverts, though their configuration may be that of a multi-girder, box culvert, or pipe(s). Figure 3-53 illustrates the use of FRP for culverts. This has traditionally been a very competitive market; however, there may be situations when a light, easy-to-install FRP system has advantages. For instance, these systems might be suitable for installation by in-house forces.

Figure 3-53 A small box culvert

N21. Light, sign, or signal structures

Poles and similar appurtenances may hold potential, but have not been used widely to date. Figure 3-54 shows FDOT conducting a test of a novel breakaway post base.

Figure 3-54 FDOT testing a breakaway base for an FRP pole

N22. Other

This category is reserved to track applications that are yet to be developed. Figure 3-55 illustrates the use of lightweight CFRP materials for an inspection drone. An understanding of FRP material traits opens the door to innovation such as this.

Figure 3-55 Lightweight carbon is used for this inspection drone, an emerging technology.

4 Summary of Observations and Recommendations

Team Observations

Conversations with various DOTs reinforced that their interest in FRP as a bridge material varied considerably. Some sought to correct deterioration brought on by steel corrosion in their existing bridges, while others needed to improve structural members that had some design deficiency. Some DOTs liked the appeal of new components or entire structures that would have a long service life.

Use of FRP varies as does the practice of bridge engineering from one region to another. An organization's priorities, the age and condition of their infrastructure, and weather and maintenance history all lead to a variety of needs that FRP may help address. The following observations and recommendations are provided for consideration and possible action by T6.

Successful Strategies

FRP infrastructure applications can be considered mature and practice-ready if there has been enough analysis and laboratory testing to validate a scientifically sound design, there is sufficient positive experience, guidance, and training for each phase of the FRP's life (i.e., material qualification, design, construction, inspection, maintenance, and repair), and there is a method for ensuring quality. Although these items do not exist for every scenario where FRP can be used, some applications have been researched, applied, and accepted so widely that their development can be considered a success. For instance, engineers have embraced FRP bonded to concrete as a fairly standard practice. It is used to repair, strengthen, protect, and/or modify the behavior of concrete structural members (e.g., to enhance ductility). AASHTO members have been active in this area and have been the beneficiary of the ACI's extensive efforts.

Repair Damaged Structures

FRP repair or strengthening of concrete can provide a cost-effective alternative when:

- A bridge must be kept in service.
- Posting with a load restriction is not desirable.
- The detour is long.
- A bridge cannot be demolished or replaced.

When a truck hits and damages a concrete bridge, FRP can be obtained and installed relatively quickly to keep the bridge in service. The repair is often considered permanent; however, it can also be used to provide an extra measure of safety or to help buy time until a long-term solution can be devised and implemented.

An FRP repair can be done expeditiously, thus with little disturbance to traffic. Most FRP repairs can be done "under traffic" (i.e., without removing the live load being carried). This is due to the relatively slow rate at which molecular cross-linking occurs in the polymer matrix.

Visually, repaired concrete members are almost indistinguishable from the original concrete, preserving the structure's original character and preventing the public from having unwarranted concerns that they might have if the repairs were more apparent.

Retrofit Existing Structures

Seismic performance, both strength and ductility, can often be enhanced by adding confinement, shear, and flexural reinforcement externally to concrete substructure elements. Concrete girders that need additional shear or flexural capacity usually can be improved with bonded CFRP systems. This need may be due to a design error, heavier-than-anticipated live loads, or a better understanding of concrete behavior reflected in newer design specifications.

Preserve Cultural Resources

Unique assets like historic bridges can benefit from FRP because concrete repairs can be done without significantly altering the assets' appearance (see Figure 4-1). An FRP deck can help preserve steel heritage structures because their light weight can maintain and sometimes improve the live load capacity, while the solid surface provides protection to the structural elements underneath.

Figure 4-1 A historic concrete arch that was rehabilitated with FRP

Capitalize on Constructability and Service-Life Benefits

CFRP P/S strands can virtually eliminate corrosion as a concern. Corroded steel P/S strands in adjacent box beams and concrete girders have been a serious issue due to certain design details and the use of deicing salts; FRP can be used to address this problem. Similarly, new piles pretensioned with CFRP seem to be ideally suited for projects in coastal environments.

Since concrete bridge decks are exposed to traffic, water, temperature fluctuations, and often deicing salts, they can degrade rapidly once corrosion initiates in steel reinforcing. Design of concrete deck with corrosion-resistant GFRP reinforcement can provide a long-lasting deck because it is not subject to corrosion.

New structural members of FRP, such as beams, slabs, decks, and arches promise to be long-lasting because of their corrosion resistance. They also have the benefit of their light weight and ease of installation.

Pedestrian bridges, at remote sites are attractive because they can be assembled on-site with light-duty equipment. They have also been found to be cost-competitive.

FRP scuppers, downspouts and other drainage elements provide a drainage system that is much more durable than steel or PVC.

FRP materials can be used in many other ways for transportation infrastructure. Further research, development of guide specifications, and similar work will be needed before engineers can feel comfortable specifying FRP materials so DOTs can take advantage of their benefits more extensively.

Barriers to more Widespread Use

Proprietary Nature of Products

Transportation agencies have not had the expertise in-house to devise their own nonproprietary systems that make use of composite materials' unique properties, so the development of products for transportation infrastructure has defaulted to companies that are motivated by profit. Since government entities have a fiduciary responsibility to seek best value when acquiring products or services, the procurement process is not conducive to the specification of proprietary products. This presents a barrier, but it is not insurmountable since owners can use performance, rather than prescriptive, specifications to satisfy the need for competition and be assured that the taxpayers get the best value.

AASHTO could also consider producing specifications for standard products that can compete with what FRP manufacturers can produce. FRP reinforcement, for instance, is not standardized like steel; it is currently produced according to each company's proprietary design. Currently, ACI's Subcommittee 440-0K[75] and ASTM's Subcommittee D30.10[76] are working to develop a specification for GFRP concrete reinforcement.

Design Code Limitations

States look to AASHTO to set the standard for bridge practice. Based on the scan team's discussions with engineers, the lack of AASHTO guidance presents an obstacle to wider use of FRP. Potential users want to be sure that they are applying FRP materials correctly and consistently, so they look to AASHTO for specifications or guidelines, commentary, training, and design examples to go by. Development and execution of a strategic deployment plan would fill the knowledge gaps, but it would also reduce the exposure to professional liability that is associated with not having design standards to follow. Researchers and industry have an important role to play when AASHTO addresses this need. Similar guidance is needed for other phases of an FRP products' life (i.e., construction, inspection, maintenance, and repair).

Limited Design Examples

Engineers find examples especially useful when beginning to design something for the first time. In fact, they have a professional responsibility to work only within their area of expertise, so training and associated examples are essential for expanding FRP use in civil engineering projects. Some examples of repair and strengthening concrete are available; more on the design and detailing of GFRP reinforcing bars would be useful. Sample design calculations and commentary for less common uses and standalone FRP systems are especially needed.

Training

A common thread seemed to be that when a state had achieved a high level of success with a certain FRP technology, an individual had championed the effort either within the DOT or at a research institution that partnered with the agency. This cutting-edge expertise certainly enables success; however, institutionalizing the practice will need training on a wider scale within an organization. Since courses on composites are not part of a typical civil engineering curriculum, most practicing engineers do not have the background to work with FRP. In fact, bridge inspectors generally do not have the education, experience, or training to make

75 440-0K – FRP-Material Characteristics, 440 Subcommittees, American Concrete Institute, https://www.concrete.org/committees/directoryofcommittees/acommitteehome.aspx?Committee_Code=0000440-0K

76 Subcommittee 30.10 on Composites for Civil Structures, ASTM International, https://www.astm.org/COMMIT/SUBCOMMIT/D3010.htm

informed judgments about the integrity, condition, and structural performance of FRP used on bridges. Additional training opportunities would boost the level of expertise within DOTs and, subsequently, the quality of FRP applications.

Performance History

There is a relatively short history of FRP use on highway structures. Even in cases where there is field experience to validate research, performance under service conditions and over time has not been uniformly measured, tracked, and analyzed. Despite FRP's 65-year history, it is important to collect and analyze hard data to solidify the assertions made about long-term performance of infrastructure uses. The FAST Act was passed in late 2015. Its provision for assessing the performance of innovations deployed as part of IBRC is an example of the effort that is needed for the profession to benefit from past experience.

Research

Proper application of the technology and the identification of new, rewarding uses can come from a comprehensive, coordinated research program. No such program exists today. IBRC demonstration projects conducted in the early 2000s relied heavily on the experience and advice of vendors, sometimes with mixed results. While much can be learned from monitoring these outdoor laboratory applications, little data has been harvested for analysis.

AASHTO has used the NCHRP program to complete several FRP-related applied research projects, but it is not clear that these projects are part of a larger plan with strategic objectives or that some sort of road map that is being followed.

At the 2016 annual meeting of the TRB, FHWA's report on research being conducted by Turner Fairbank Highway Research Center[77] contained no reference to FRP. This may be perceived as a lack of progress, activity, or leadership.

A more active T6 could become more specific and vocal in expressing its needs and research interests. For instance, closer collaboration between AASHTO SCOBS T6 and T10[78] (Concrete) could result in the building of momentum to include FRP reinforcement into the AASHTO LRFD Bridge Design Specifications[79]. Inclusion in the specifications is necessary if FRP is to be recognized as an alternative material for transportation infrastructure.

Information Sharing

When states perform their own research, the results can be shared by making the reports available through TRB's Transportation Research E-Newsletter[80]. These published reports are valuable, especially to a transportation agency that wishes to venture into areas where it has little experience. What is frequently lacking, however, is access to information about completed projects, such as specifications, details, cost data, quality control measures, and performance results.

Availability of Materials and Systems

Unlike concrete and steel, the materials conventionally used in civil engineering projects, the number

77 Federal Highway Administration Research and Technology, Federal Highway Administration, U.S. Department of Transportation, http://www.fhwa.dot.gov/research/

78 SCOBS-T-10 Concrete Design Committee, AASHTO Subcommittee on Bridges and Structures, American Association of State Highway and Transportation Officials, http://bridges.transportation.org/Pages/T-10ConcreteDesign.aspx

79 AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 7th Edition, with 2015 and 2016 Interim Revisions, American Association of State Highway and Transportation Officials, https://bookstore.transportation.org/item_details.aspx?id=2211

80 TRB Transportation Research E-Newsletter, Transportation Research Board, The National Academies of Sciences, Engineering, and Medicine, http://www.trb.org/Publications/PubsTRBENewsletter.aspx

of suppliers and the availability of FRP are somewhat limited. The National Ready Mixed Concrete Association[81] estimates that there are about 5,500 ready mixed concrete plants that produce concrete and about 55,000 ready mixed concrete mixer trucks that deliver it to the point of placement[82]. In contrast, the number of companies currently producing FRP products for use in civil engineering projects is a few dozen. Composite materials have become mainstream in the aerospace, military, boating, and sporting goods industries, yet low demand in the transportation industry has contributed to a weak supply chain.

Lessons Learned

Experience provides an opportunity to learn from what has gone well and what can be improved.

Total Project Cost Trumps High Material Cost

The initial cost of FRP material is often cited as a barrier to more widespread use; however, owners and contractors are finding that their use can result in a lower project cost. For instance, repairing a damaged concrete member will cost much less that replacing it. In addition, it can be done faster. As the adage goes, time is money.

When initiating a project, an owner may compute a benefit/cost ratio or annualized cost to compare alternative approaches to the problem. A rapidly completed project results in lower user costs because the public suffers fewer time delays. When life-cycle costs are considered, value is added from the corrosion-resistant material's contribution to a long service life. These factors usually offset the high material cost.

Heritage Structures Can Be Addressed

The availability of composite materials makes it much easier to preserve culturally significant structures such as historic bridges. Sometimes they can provide the only reasonable alternative when the option to replace a structure does not exist. Deteriorated concrete arches have been restored and improved with FRP without significantly altering the structure's appearance. This is an extremely important benefit because a state historic preservation officer is apt to endorse such context-sensitive treatment.

Decks Have Been a Challenge

Eliminating ferrous corrosion as a failure mechanism in bridge decks would greatly extend the service life of this critical bridge element, so it is logical that bridge owners would be interested in using FRP as a deck. Most of the 100+ installed FRP decks are functioning as intended, but some have required much more maintenance than anticipated. Some had flaws deemed irreparable and have been taken out of service. The setbacks in the deployment of this application have made some engineers wary, not just of FRP decks, but possibly FRP in general.

QA/QC Is Critical

Proper design, detailing, and installation are critical to the success of a project. For example, during construction, if CFRP is wrapped around a rectangular concrete column without smoothing and rounding the corners, there is likely to be fiber damage and premature failure at that location.

Partnerships Are Better than Outsourcing

The scan team observed that the best overall progress was made where a DOT partnered with an expert

---

81 National Ready Mixed Concrete Association, http://www.nrmca.org/

82 Ready Mixed Concrete Production Statistics, National Ready Mixed Concrete Association, https://www.nrmca.org/concrete/data.asp

researcher at a university. Early attempts at deployment of FRP technology for public works projects relied heavily on the knowledge of industry, since there was little expertise within the ranks of DOT organizations. DOTs sometimes took a hands-off approach to design, installation, and QA/QC and, instead of funding their own research and qualification programs, relied on suppliers' certifications.

Although many industrial partners were competent in the area of composites, most had had no experience designing for the harsh demands that are placed on highway structures from live loads, weather extremes, and unexpected events, such as collision and fire. This inexperience and lack of partnership resulted in problems that might have been avoided. The American Composite Manufacturers' Association[83] (ACMA) is a representative of industry that is available for collaboration[84].

Knowledge Gaps Exist

Although FRP has been used quite extensively and guidelines for its use are evolving, discussions with users show that some technical issues still need to be worked out. A strategic approach to research needs should be explored, possibly as part of an FRP users' workshop guided by T6.

Some critical concepts also need additional clarification and emphasis to ensure that FRP is used appropriately. To increase awareness, these important points should be explicitly highlighted in any training and emphasized in webinars that feature case studies and best practices. For example, it may seem intuitive that additional layers of fiber in a bonded FRP system will add strength; however, that notion is not entirely accurate, because the system strength may be governed by the strength of the adhesive bond. Adding too many layers may even be harmful because it can change the failure mode.

Recommendations

The scan team has identified actions that will allow FRP to become another tool in the tool chest of DOT managers and engineers. The following suggestions are made to share the benefits of using FRP, to increase the knowledge base so that FRP can be judiciously and effectively deployed, and to address barriers that exist.

Strategy

AASHTO T6 may be able to use this report at the start of a strategy to address the needs and knowledge gaps that have been identified. This can be used as a road map for future research and development of necessary guidelines and training.

Information Sharing

There is no comprehensive record of how DOTs have used FRP and how the systems are performing, so it would be in AASHTO's interest to track usage and performance and share this information. T6 may want to recommend a uniform method of recording inspection information for FRP on an element-level basis. This will evolve into a means of inventorying use and tracking performance.

The team discovered that information about completed FRP projects was not readily available to bridge inspectors and others who might need it. Especially for future analyses, it is important to know what products have been applied and what the material properties were in the beginning. The materials used, design calculations, construction methods, and maintenance records need to be documented as with any other structural modification, and the information should be accessible to those who need it.

83 American Composite Manufacturers Association, http://www.acmanet.org/

84 CGI (Composites Growth Initiatives) Committees, American Composite Manufacturers Association, http://www.acmanet.org/cgi-committees

Sharing information about completed projects is important. Communicating experiences helps new users, but also facilitates continuous improvement of applications among more experienced users. Some states already have a good record of FRP case studies, guidelines, and standards on their own websites. A collection of the state URLs on FHWA's existing FRP pages could comprise a virtual comprehensive library of project information, providing a focal point for dissemination of infrastructure-specific FRP knowledge. Leveraging the value of information that has already been produced is a logical way for AASHTO to expand the knowledge base without redundant effort.

Since the FAST Act requires that the performance of IBRC-funded projects be assessed, the opportunity exists to attain some of the data that has been lacking. AASHTO SCOBS T6 should partner with FHWA and the industry in collecting and evaluating data that will help quantify FRP's benefits. Drawing from almost 15 years of field experience, states are also in the best position to make recommendations about using this technology to extend bridge service life.

Publications

The scan revealed that it may be necessary to review existing AASHTO publications to determine if they need to be updated to account for changes, improvements, and research that have occurred since they were first published. During this reassessment, ensure that any research that is done in support of the guidelines is based on realistic scenarios that might be expected under service conditions. Look for opportunities to test FRP that has been in service for a period of time to help determine what is rational to use for environmental factors.

Standard Designs

AASHTO should strive to achieve some standard designs because increased competition on a common product will bring prices down. Proprietary designs have the opposite effect. The use of standard AASHTO girder designs is an example of this competitive approach. To start, the team suggests that CFRP strengthening systems be codified. This would establish a benchmark system, not to stifle creativity, but to create a consistency among installations that would allow an owner to know what to expect each time.

Collaboration

Collaboration is an effective way to leverage resources. By working closely with FHWA in particular, T6 can provide support to FHWA's internal FRP champion (scan team member Jamal Elkaissi). This champion can coordinate communication and activity among government, industry, and academia to advocate for the R&D of standards that are needed for the advancement of FRP.

Together, AASHTO and FHWA could form a virtual FRP team, organize an FRP summit, establish a users' group, utilize programs such as Every Day Counts and AASHTO's AII to demonstrate maturing applications, and much more. A national initiative launched through Every Day Counts[85] and AII could help jump-start interest. For example, a project that demonstrates the use of GFRP reinforcement in a concrete deck and disseminates the information as a case study would be an effective way to educate engineers about why and how to use GFRP bars. These programs would be an effective way to promote specific FRP best practices and reap "low-hanging fruit."

An owners users' group would encourage informal discussion where good and bad experiences can be shared, advice can be given and received, immature ideas can be brainstormed, unpublished information can be exchanged, and needs can be expressed. These items are not typically presented in research

85 Every Day Counts, Center for Accelerating Innovation, Federal Highway Administration, U.S. Department of Transportation, http://www.fhwa.dot.gov/innovation/everydaycounts/

papers or engineers' presentations at conferences. A users' group that meets virtually, if not in person, would undoubtedly improve communication among states and other asset owners. Consider using "bridge preservation partnerships" as a way to have personal interaction.

Engaging with industry also has many advantages. DOT engineers can benefit from manufacturers' specialized knowledge and learn about materials, techniques, and products developed for other market segments. Aerospace, military, boating, and recreational industries have achieved a high level of success with FRP, so looking for crossover FRP technology that can be transferred to infrastructure applications may create an opportunity to adopt a modified version of technology that was originally developed for a totally different market segment.

Established industries (e.g., steel and concrete) have associations and institutes that effectively promote their products by continuously improving practice. They are involved in research, setting standards, developing designs, educating users, and raising awareness. The FRP industry, which is generally represented by ACMA, has a smaller network that can be called on to communicate with transportation agencies. There is no "Institute for FRP in Transportation" in the U.S.

Sustainability

The benefits of an FRP project alternative can often be demonstrated by considering the value of travelers' time, the speed of construction, and energy costs. In the future it will be more and more common to consider the carbon footprint of one alternative over another and the level of CO2 emissions associated with each. Initiate studies to quantify the environmental benefits of FRP versus alternatives. In the future, a project's carbon footprint (i.e., the environmental cost) might be considered as significant as its financial cost.

Training

Outline an educational program to raise the level of expertise among DOT staff, installers, and others. This should be dictated by the needs of AASHTO members, though collaboration with NHI, universities, and others will be needed to develop and deliver its various components. Take advantage of actual projects to produce training videos, as is common on the Internet (e.g., YouTube or Vimeo).

Since many bridges in service already use FRP, it is imperative that training be provided to the inspectors and people who maintain these structures. Even if it will take time to produce the needed training, a plan can be developed that details what is needed.

- **Organize an FRP summit**—A focused workshop may be needed to help T6 summarize, assess, and document current practice and research. Stakeholders such as FHWA, other AASHTO Standing Committee on Highways subcommittees, industry, academia, and local bridge owners could provide valuable input.
- **Develop an education curriculum**—Determine what knowledge and skills are needed for designers, contractors, inspectors, and maintainers and develop training courses to satisfy those needs.
- **Develop training videos**—Traditional classroom training courses or web-based training may be needed, but the use of video technology should be considered for the sake of expediency. After developing an outline of questions that are typically asked, AASHTO could identify experts who could answer the questions in a three- to five-minute video, using illustrations, if suitable. The video of experts (or stand-in narrators) could be posted on YouTube, Vimeo, or other sites to make it widely accessible.
- **Host webinars**—Webinar technology has been used successfully to present case studies and recent

research. A similar approach could stimulate conversations about FRP use.

Dissemination of Information

Contained in this document are URL links that states and others have provided. **Use of company or proprietary product names in the URL or elsewhere in this document is not an endorsement by the author, the scan team members, or the TRB.**

Appendices are provided to share the information bulleted below, with the understanding that the information is just a snapshot at one point in time and may need to be refreshed over time.

- Appendix G—Identification of lead states, those with the most experience in an application
- Appendix F—Identification of researchers who are on the forefront of individual FRP applications
- Contact information for the scan team members (Appendix B) and individuals at state DOTs (Appendix D) who are active in certain areas of FRP use.
- Appendix J—A list of research documents for deeper exploration of related topics.

This report can be downloaded from the U.S. Domestic Scan Program website[86] and will be disseminated through the scan team's and AASHTO SCOBS T6's outreach efforts. Scan team members will provide a summary of the team's findings at technical conferences and meetings within their home state as well as nationally. The information obtained will be readily available to FHWA, state DOTs, local bridge owners, authorities, federal and local agencies, FRP industry manufacturers, university researchers/students, and consultants. Team members will look for opportunities to communicate the findings locally and at the national level. The material will also be presented to students of CIE-580 Emerging Technologies in Bridge Engineering, a graduate-level class at the University at Buffalo.

Implementation of the Recommendations

"Use it where you need it!" is an expression that the scan team repeatedly used; its members suggest that asset owners adopt this as a rule of thumb when considering FRP. The team feels strongly that FRP use should be need-driven. It is probably not the most appropriate choice if there is a faster or less expensive way to accomplish the same thing. In an even-handed assessment, the obvious choice will usually surface.

AASHTO initiated this study to find out how its members have been using FRP and what gaps need to be filled to make it a viable option when specifying materials for projects in the future. This report identifies some activities that will advance the state of the practice. Implementation of those recommendations will likely rely on AASHTO SCOBS T6 due to its charge and accumulated expertise. Other engineers, such as operations staff and local bridge owners, will undoubtedly use the products (e.g., documents and training) developed under SCOBS's direction, but will depend on SCOBS to lead the effort.

With the recent increase in design-build (DB) and public-private-partnership projects, states will soon need a set of standards that can be applied when a DB team proposes using FRP. FRP is likely to be attractive because of the ease and speed of installation (resulting in lower cost to the DB team). Long-term durability is obtained from its corrosive-resistant nature; reduced maintenance will be especially desirable to DB firms responsible for operating the facility after its construction.

86 U.S. Domestic Scan Program, http://www.domesticscan.org/

It would not be unusual for a DB team to be responsible for maintaining a built facility for a 30- to 35-year period before handover to the owner agency. Sufficient research and standards development are needed to mitigate the risk associated service life beyond that timeframe. The owner must have the ability to accurately predict FRP's long-term performance.

Appendix A:
Scan Team Biographical Sketches

WAYNE FRANKHAUSER, JR. (AASHTO CHAIR) is the Bridge Program manager for the Maine Department of Transportation (MaineDOT). Frankhauser leads the Bridge Program, which is responsible for the design, project management, utility coordination, right-of-way appraisal and negotiations, structural fabrication, and construction management for all capital bridge projects developed by MaineDOT. He has been with MaineDOT for 22 years and has served as bridge designer and project manager. Frankhauser currently chairs the AASHTO SCOBS T-6 Technical Subcommittee on Fiber-Reinforced Polymer Composites and is a member of the T-9 Technical Subcommittee for Bridge Preservation. He is a graduate of the University of Maine with a bachelor's degree in civil engineering and is a licensed professional engineer in Maine.

JAMAL ELKAISSI is a structural engineer with FHWA who serves on the Resource Center's Bridge Design and Construction Structures Team in Colorado. He draws from over 20 years' experience in bridge design, rehabilitation, and construction inspection, including complex bridges located in high seismic zones. He is a member of AASHTO T-6 Technical Committee on Fiber Reinforced Polymers and TRB AFF80 Structural Fiber Reinforced Polymers Committee. He was team lead for the development of three computer-based NHI training courses: Introduction to FRP Materials and Applications for Concrete Structures, Construction Procedures and Specifications for Bonded Repair and Retrofit of Concrete Structures, and Quality Control of Repair and Retrofit of Concrete Structures Using FRP Composites. Elkaissi earned his bachelor's degree in civil and environmental engineering and a master's degree in structural engineering at the University of Colorado and is a licensed professional engineer in Colorado.

STEVEN KAHL is manager of the experimental studies group for the Michigan Department of Transportation (MDOT) at the Construction Field Services office in Lansing. His group performs structural investigations on bridges, culverts, roadside features, and structural materials and components. For 10 years, Kahl has been involved with FRP research and FRP specification development and implementation. He currently manages several university research Centers of Excellence, focusing on advanced topics in bridge engineering. Kahl has been with MDOT for 20 years, holds a bachelor's degree in both civil and chemical engineering from Michigan State University and is a licensed professional engineer in Michigan.

STACY McMILLAN is a structural liaison engineer with the Missouri Department of Transportation. In this position he provides project management, guidance to consultants, and expertise in structural matters, including the implementation of rehabilitation, preservation, and replacement strategies pertaining to design, construction, and inspection of highway structures. McMillan was the bridge engineer for Missouri's Safe and Sound Bridge Improvement Program, which replaced or rehabilitated over 800 bridges in five years. He is a graduate of Kansas State University and a licensed professional engineer in Missouri.

WILLIAM (WILL) POTTER is the manager of the M.H. Ansley Structures Research Center for the Florida Department of Transportation in Tallahassee. In this position he manages and oversees many aspects of structures research and testing through in-house projects and contracted projects with various academic partners. He also manages the bridge load testing program throughout the state. He is a current member of the AASHTO SCOBS T-6 Technical Subcommittee on Fiber-Reinforced Polymer Composites. He received his bachelor's and master's degrees in civil engineering from Florida State University. He is a licensed professional engineer in Florida.

DAVID RISTER is the state bridge construction engineer for the South Carolina Department of Transportation (SCDOT) in Columbia. His primary duties include administering the state bridge construction program, supporting preconstruction and maintenance activities related to bridge construction and repair, and assisting with structural products evaluation. He has been with SCDOT for over 20 years, holding positions in bridge design, bridge program management, and bridge construction. He holds a bachelor's degree in civil engineering from of Clemson University and a master's degree in civil engineering from the University of South Carolina. He is a licensed professional engineer in South Carolina.

DeWAYNE WILSON is the bridge asset management engineer for the Washington State Department of Transportation (WSDOT). His primary duties include supervision of the Asset Management Unit, which is tasked with identifying and prioritizing the preservation needs for the 3,239 state-owned bridges. He works with others in the WSDOT Bridge Office to identify initial scopes of work for the bridge preservation projects, including repairs and rehabilitations that may use FRP materials. He has been with WSDOT for 31 years, having done bridge inspections and managing the department's Bridge Deck Rehabilitation Program. He has been in his current position for 11 years. He holds a bachelor's degree in civil engineering and is a licensed professional engineering in the state of Washington.

JEROME O'CONNOR (SUBJECT MATTER EXPERT) is the executive director of the Institute of Bridge Engineering, University at Buffalo (UB). He worked as a bridge management engineer for the latter half of his 20 years at New York State DOT. In that role, he became recognized as a champion for the use of FRP on bridges. In 2002, he joined MCEER, the earthquake research center at UB to serve as project manager for its FHWA-funded research projects. He earned both his bachelor's and master's degrees from Rensselaer Polytechnic Institute, with a focus on transportation engineering. He is an ASCE Fellow and licensed professional engineer in New York State, Puerto Rico, Pennsylvania, Hawaii, and Kansas.

Appendix B: Scan Team Contact Information

Wayne Frankhauser, Jr., PE, AASHTO Chair
AASHTO T6 Chair
Assistant Program Manager, Bridge Program
Maine Department of Transportation
16 State House Station
Augusta, ME 04333
Phone: **(207) 557-8924**
E-mail: wayne.frankhauserjr@maine.gov

Jamal Elkaissi, PE, MS
Civil (Structural) Engineer- Bridge Design and Construction
Structure Team- Resource Center, FHWA
12300 W Dakota, Suite 340
Lakewood, CO 80228
Phone: **(720) 963-3272**
E-mail: jamal.elkaissi@dot.gov

Steven Kahl, PE
Supervising Engineer
Experimental Studies Group
Operations Field Services Division
Michigan Department of Transportation
8885 Ricks Road
Lansing, MI 48917
Phone: **(517) 322-5707**
Fax: **(517) 322-5664**
E-mail: kahls@michigan.gov

Stacy McMillan, PE
Structural Liaison Engineer, Bridge Division
Missouri Department of Transportation
105 W. Capitol Avenue
Jefferson City, MO 65102
Phone: (573) 526-0250
E-mail: stacy.mcmillan@modot.mo.gov

William Potter, PE
Florida Department of Transportation
M.H. Ansley Structures Research Center
2007 E. Paul Dirac Drive
Tallahassee, FL 32399
Phone: **(850) 921-7106**
(850) 921-7100
E-mail: william.potter@dot.state.fl.us

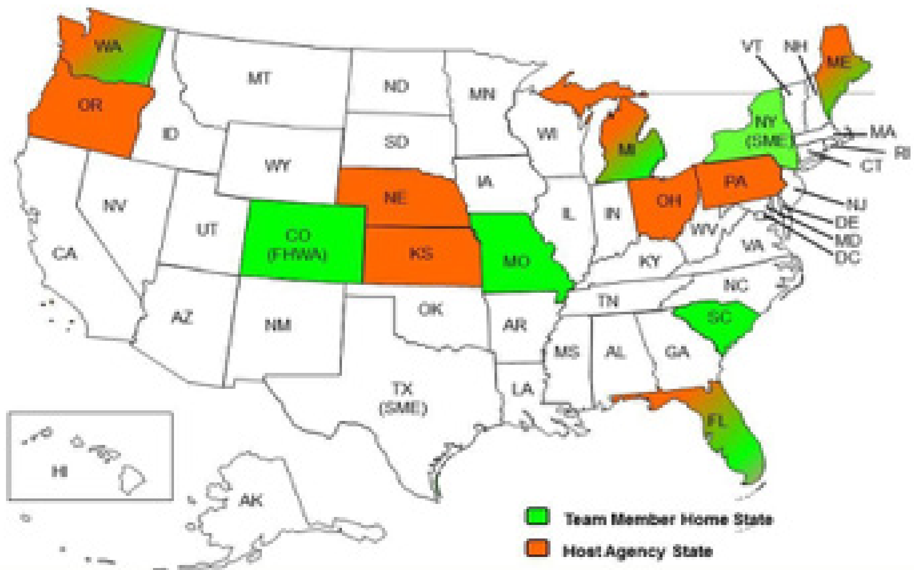
David Rister, PE
Bridge Construction Engineer
South Carolina Department of Transportation
PO Box 191
Columbia, SC 29201
Phone: **(803) 737-1490**
E-mail: ristergd@scdot.org

DeWayne Wilson, PE
Bridge Asset Manager
Washington State Department of Transportation
PO Box 47340
Olympia, WA 98504-7340
Phone: **(360) 705-7214**
E-mail: wilsond@wsdot.wa.gov

Jerome S. O'Connor, PE, FASCE, Subject Matter Expert
Executive Director
Institute of Bridge Engineering
Dept. of Civil, Structural and Environmental Engineering
228 Ketter Hall
University at Buffalo
Buffalo, NY 14261
Phone: **(716) 645-5155**
E-mail: jso7@buffalo.edu

Melissa (Li) Jiang, Scan Coordinator
Arora and Associates, P.C., Consulting Engineers
Princeton Pike Corporate Center
1200 Lenox Drive, Suite 200
Lawrenceville, NJ 08648
Phone: **(609) 482-2642**
(609) 844-1111, Ext. 1142
Fax: **(609) 844-9799**
E-mail: mjiang@arorapc.com

Appendix C: Scan Itinerary



Week #1

May 31 to June 3, 2015: Maine Department of Transportation

Sunday, May 31

Fly to Portland, Maine

7:00 – 8:00 pm	Initial team meeting

Monday, June 1

8:00 – 8:30 am	Travel to Brunswick, ME
8:30 – 11:30 am	Meet with Harbor Technologies
11:30 – 12:30 pm	Lunch
12:30 – 1:00 pm	Travel to Augusta, ME
1:00 – 4:00 pm	Meet with Kenway Corporation

Field visit to Westbrook, Bridge St or Thomaston, Wadsworth St depending on construction schedule. Both are HC Beam bridges.

Tuesday, June 2

7:30 – 7:45 am	Travel to MaineDOT
7:45 – 11:00 am	Meet with MaineDOT staff Scan Team/MaineDOT Q &A and presentations on: ■ Composite pile testing – Laura Krusinski ■ Hybrid Composite beams – Nate Benoit ■ Composite Arches – Nate Benoit, Robbin Lanpher & Dale Peabody ■ Composite bridge drains – Michael Wight ■ Carbon fiber prestressing and post-tensioning – Leanne Timberlake & Mark Parlin ■ GFRP rebar – Mark Parlin ■ Composite culvert rehabilitation – Devin Anderson
11:00 – 12:15 p.m.	Travel to Bangor, ME
12:15 – 1:00 pm	Lunch
1:00 – 3:00 pm	Meet with Advanced Infrastructure Technologies
3:00 – 3:30 pm	Travel to Lagrange, ME
3:30 – 4:30 pm	Field visit – Lagrange composite bridge

Wednesday, June 3

7:45 – 8:00 am	Travel to UMaine
8:00 – 11:00 am	Meet with UMaine Advanced Structures & Composites Center
11:00 – 12:15 pm	Lunch and travel to Bangor, ME
12:15 – 1:15 pm	Field visit – Bangor, Union Street Bridge HC Beams
3:30 pm	Flight from Bangor to Tallahassee

Thursday, June 4

Florida DOT, FDOT Central Office – Suwannee Room

11:00 am – 11:45 am	Will Potter Introduction/Discussion
11:45 am – 1:00 pm	Lunch
1:00 pm – 1:45 pm	Rick Vallier/Charles Boyd Composites and FDOT Direction
1:45 pm – 2:15 pm	Steve Nolan Implemented Design Standards
2:15 pm – 2:30 pm	Break
2:30 pm – 3:15 pm	Chase Knight Materials Aspect
3:15 pm – 3:45 pm	Will Potter FRP Bridge Deck Case Study
3:45 pm – 4:15 pm	Will Potter Structures Research
4:15 pm – 5:00 pm	Elisha Masseus / Mamum Siddiqui, Halls River Bridge Project

Friday, June 5

Florida DOT, FDOT Central Office

AM – FDOT Central Office – Suwannee Room

PM – FDOT M. H. Ansley Structures Research CenterTime Presenter Topic

8:00 am – 8:45 am	Dr. Mohsen Shahawy – SDR Work and Accomplishments
8:45 am – 9:30 am	Dr. Antonio Nanni – UM Work and Accomplishments
9:30 am – 10:15 am	Dr. Rajan Sen – USF Work and Accomplishments
10:15 am – 10:30 am	Break
10:30 pm – 11:15 am	Dr. Amir Mirmiran – FIU Work and Accomplishments
11:15 am – 12:00 pm	Dr. Trey Hamilton – UF Work and Accomplishments
12:00 pm – 1:30 pm	Lunch
1:30 pm – 5:00 pm	Will Potter Structures Lab Tour and Structures - Research Items

Week #2:

Monday, July 13

Lawrence Technological University, Southfield, MI

TIME	PERSON	TOPICS
9:00–9:15 am	All	Introductions/Scan purpose
9:15–10:00 am	M. Chynoweth	■ Ongoing Michigan research on CFRP ■ Ongoing National research on CFRP ■ Expected AASHTO design guidelines codification ■ AASHTO Innovations Initiative - Carbon Fiber Prestressing Lead States Team Status
10:00–11:30 am	Dr. N. Grace	■ Comprehensive presentation of FRP research, design, and implementation ■ CFCC design and testing requirements

11:30–Noon	MDOT staff/scan team roundTable discussion and Q&A	■ MDOT Bridge Design – design and plan preparation for CFRP
12:00–12:45 pm	ALL	Lunch (at LTU)
12:45–1:30 pm	Dr. C. Eamon	Presentation of WSU research on FRP design, maintenance, and construction guidelines
1:30–2:15 pm	Dr. N. Grace	Lab tour, discussion of testing
2:15–4:00 pm	ALL	Field visit to M102 or Bridge St. Structures

Wednesday, July 15

OR – WA Visit, WSDOT SW Regional Office, Vancouver, WA; 11018 NE 51st Circle, Vancouver, WA 98682-6686 Phone: 360.905.2000

Oregon DOT Presentations

8:00 am	Introduction, ODOT Use of FRP Overview	Bruce Johnson
8:15 am	GFRP Rebar, Millport Slough Bridge and Lewis & Clark River Bridge	Matthew Stucker
8:45 am	Near Surface Mount research and application	Dr. Chris Higgins, OSU
9:30 am	Shear and Flexure Strengthening of RCDG bridges	Dr. Chris Higgins, OSU
10:00 am	Break	
10:15 am	CFRP Inspection and performance evaluation	Jeff Swanstrom
10:45 am	FRP Bridge Deck applications	Ray Bottenberg
11:15 am	Multnomah County FRP Bridge Deck Applications	Ken Huntley
11:45 am	Description and preparation for Field Visits	Bruce Johnson

Site Visit in Oregon

1:00 pm	Site Visit to Broadway Bridge, Portland (FRP Deck)	Ken Huntley
2:00 pm	Site Visit to Morrison Bridge, Portland (FRP Deck)	Ken Huntley
3:30 pm	Site Visit to Horsetail Falls Bridge and Oneonta Creek Bridge; Historic Columbia River Highway (FRP Strengthening)	Bruce & Ray
5:30 pm	Arrive at the Hotel in Portland	

Thursday, July 16

OR – WA Visit, WSDOT SW Regional Office, Vancouver, WA; 11018 NE 51st Circle, Vancouver, WA 98682-6686 Phone: 360.905.2000

Site Visit in Oregon

8:00 am	Travel to Columbia Gorge sites 2nd Street Bridge, Hood River – FRP Strengthening I-84/Rock Creek, Mosier – FRP Strengthening Mosier WB Connection over I-84 – Titanium Near Surface Mount	Bruce & Ray
11:30 am	Arrive at WSDOT SW Region Office	
Noon	Lunch	

Washington State DOT Presentations

1:00 pm	Seismic Retrofit of Historical Bridge Columns Using Fiber Reinforced Polymer	Craig Boone
2:00 pm	CFRP Strengthening of SR-520 Floating Replacement Bridge Sam Yao	
3:00 pm	Alaskan Way Viaduct FRP Strengthening	Tim Moore

4:00 pm	Wrap up discussion	

Friday, July 17

OR – WA Visit, WSDOT SW Regional Office, Vancouver, WA; 11018 NE 51st Circle, Vancouver, WA 98682-6686 Phone: 360.905.2000

8:00 am	**Webinar:** Presentation by PennDOT (11am - 12:45pm Eastern Time)	Guozhou Li
9:45 am	Break	
10:00 am	**Webinar:** Presentation by Ohio DOT (1pm - 2:45pm Eastern)	Tim Keller
Noon	Lunch	
1:00 pm	Presentation by Nebraska DOR	Mark Traynowicz & Joel Rossman
2:45 pm	Break	
3:00 pm	Presentation by Kansas DOT	Calvin Reed & Mark Hurt
4:45 pm	Wrap up discussion	

Appendix D: Host Agency Contacts

Speakers	Host Agency	Contact
• Maine DOT – Wayne Frankhauser, Jr. – Laura Krusinski – Nate Benoit – Robbin Lanpher – Dale Peabody – Michael Wight – Leanne Timberlake – Mark Parlin – Devin Anderson • Harbor Technologies, Inc. • Kenway Corporation • Advanced Infrastructure Tech. • Dr. Habib Dagher, UMaine	MaineDOT	Wayne Frankhauser, Jr. (wayne.frankhauserjr@maine.gov)
• Florida DOT – Will Potter – Rick Vallier – Charles Boyd – Steve Nolan – Chase Knight – Elisha Masseus – Mamum Siddiqui • Dr. Mohsen Shahawy, SDR, Inc. • Dr. Antonio Nanni, UM • Dr. Rajan Sen, USF • Dr. Amir Mirmiran, FIU • Dr. Trey Hamilton, UF	FDOT	Will Potter (william.potter@dot.state.fl.us)
Mathew Chynoweth	MDOT	Steven Kahl (kahls@michigan.gov)
Dr. Nabil Grace Dr. C. Eamon, WSU	Lawrence Technological University	Dr. Nabil Grace (nabil@ltu.edu)
• Oregon DOT – Bruce Johnson – Matthew Stucker – Jeff Swanstrom – Ray Bottenberg • Dr. Chris Higgins, OSU	Oregon DOT	Bruce Johnson (bruce.v.johnson@odot.state.or.us)
Ken Huntley	Multnomah County, OR	Ken Huntley (kenneth.r.huntley@multco.us)
Oregon DOT • DeWayne Wilson • Craig Boone • Sam Yeo • Tim Moore	Wash DOT	DeWayne Wilson (wilsond@wsdot.wa.gov)
Guozhou Li	Pennsylvania DOT (virtual presentation)	Guozhou Li (guli@pa.gov)
Tim Keller	Ohio DOT (virtual presentation)	Tim Keller (tim.keller@dot.state.oh.us)
Mark Traynowicz Joel Rossman	Nebraska DOR (at Vancouver, WA meeting)	Mark Traynowicz (mark.traynowicz@nebraska.gov)
Calvin Reed Mark Hurt	Kansas DOT (at Vancouver, WA meeting)	Calvin Reed (calvinr@ksdot.org)

Appendix E: Amplifying Questions

1. **Tell us about your agency.**
    a. # state bridges; # local bridges; large culverts you are responsible for
    b. # staff you have for the structures program
    c. Current trends or special circumstances such as capital funding levels, maintenance needs, recent legislation, and issues
    d. Is the decision to use FRP up to you? If not, who?
2. **Highlight the types of FRP projects your agency has completed.**
    a. **How many were new bridges vs. repair/retrofit of existing?**
    b. **List, briefly describe, and quantify if possible, the projects you have undertaken with FRP, using the attached questionnaire for specifics.**
    c. **What type of documentation can you share about your completed projects?**
    d. **Is this information readily available on your website or elsewhere?**
    e. **What was the primary motivation for using FRP? Weight? Corrosion? Ease? Cost?**
    f. **What benefit were/are you hoping to get out of using FRP?**
    g. **Name the biggest benefit of FRP, or success to date.**
    h. **What do you think needs to be improved to make FRP use more common?**
    i. **Is there a "lesson learned" that you'd like to share?**
    j. **Is there additional guidance or research needed? What?**
    k. **Have you used FRP in an emergency response situation?**
    l. **What do you expect to be your predominant use of FRP in the future?**
3. **Quality**
    a. **Describe what is done to ensure quality of the finished project and over its life.**
    b. **What unanswered questions or concerns do you have about the use of FRP?**
    c. **What steps were taken to assure quality during design and construction?**
    d. **Does your agency's material specifications and approved lists include FRP?**
    e. **What do you require to be included in designer or contractor submittals?**
    f. **What training do you provide to your staff? Do you need help in this regard?**
    g. **Are your designs always certified by a professional engineer?**
    h. **Do you require that installers be certified? By whom?**
    i. **Have inspectors been given guidance so they how to evaluate and rate the condition and performance of each FRP installation when inspecting every two years?**
    j. **In addition to general bridge inspections, is any monitoring done to assess system performance over the service life of the FRP application?**
4. **How do you know that project expectations have been met? Who decides?**
    a. **Do you attempt to measure or track the benefits obtained from using FRP? If so, what metrics are used?**
    b. **Has the use of FRP saved you money over alternatives?**
    c. **Is a benefit/cost analysis done?**
    d. **Do you perform a life-cycle cost assessment to justify the use of FRP?**
    e. **Does the use of FRP usually result in an improvement in load rating?**
    f. **Do you try to extend the service life of structures? If so, by how much? How will you know if you were successful?**
    g. **Is data collected during the service life of your FRP applications?**
5. **What is done to maintain continuity of FRP use in your agency?**
    a. **Describe any steps taken to make FRP easier to include in a project (as a more**

mainstream material). Describe standards, policies, guidance....

b. Has adoption of FRP technology relied on a champion or a few internal advocates?
c. What does your agency do to stay abreast of advances in the technology and disseminate the information?
d. Is inspection and maintenance routinely done on your past FRP installations?
e. How do you communicate your FRP successes/lessons internally and nationally?

6. Do you have any other observations, comments or suggestions? Thank you!

7. Available Resources

a. A list of completed projects that used FRP
b. A copy of any construction specifications that were used
c. Cost data (per project or cost per square foot)
d. Contract plans
e. Project photos
f. PowerPoint presentations you are willing to share
g. Design software
h. Design examples
i. Checklist for designers
j. Checklist or manual for construction inspectors
k. QA/QC manual for FRP
l. Project summaries, reports, articles, websites

8. General

a. Does your agency have any policy or program to encourage the use of FRP?
b. Do you use a life-cycle cost analysis to justify the use of FRP?
c. What in-house research has been done for FRP applications?
d. Have you participated in any NCHRP or pooled-fund FRP study?
e. Have you had any FRP projects you consider a failure?
f. Do you have any advice for others who might want to use FRP?
g. Do you typically procure FRP systems as sole-source?
h. Do you feel that you have all the information you need to make a decision about using FRP? If not, what is missing?
i. Do you have the in-house support and resources you need to use FRP (encouragement, training, procedures)?
j. Do you have the external support and resources you need to use FRP (AASHTO, ACI, ASCE)?
k. Please describe any repairs or extraordinary maintenance you have had to perform on your FRP applications.
l. Where do you currently get your information about FRP?

Optional response sheets for additional details

1. Project Type

Has your agency used FRP for any of the following?	Check all that apply.	How many projects?	Fiber type: Glass	Fiber type: Carbon	Fiber type: Other
New construction					
Entire bridge or superstructure					
Bridge-in-a-Backpack					
Structural slab					
Other:					
Beams					
HC Bridge					
Timber / FRP hybrid					
Other:					
FRP deck					
FRP rebar or grid in concrete deck					
Prestressing tendon					
internal					
external					
Substructure / piles					
Fenders / sheet piling					
Architectural					
On existing structures					
Concrete repair for collision damage					
Concrete repair for corrosion damage					
Seismic retrofit					
Strengthening concrete to increase capacity					
Improving concrete deck serviceability					
Aerodynamic improvement					
Repair of other defects (specify)					
Other:					

TOTAL number of FRP projects completed $\Sigma =$

How many of the above were *not* especially successful?

How many FRP projects do you anticipate within the next 5 years?

What type of FRP project do you anticipate to use in the future?

Notes to further explain how FRP was used:

2. Materials

Check the techniques / components that your agency has used.

- o wet layup
- o pre-preg
- o pre-cured
- o near surface mounted (NSM)
- o external post tensioning
- o rebar or grid
- o prefabricated element e.g. (deck, beam)
- o other:

3. Benefit: Check all that your agency hopes to benefit from FRP.

- o corrosion resistance
- o light weight
- o high tensile strength
- o ease & speed of installation
- o little disruption to traffic.
- o installed cost is less than alternatives
- o lower life cycle cost
- o ease of conformity to the geometry of the member,
- o availability in various forms (sheets and strips)
- o other:

4. Drawbacks & Limitations

Check what concerns you

- o Cost (high initial material cost)
- o Lack of specifications, standards and design guides
- o Potential degradation due to ultraviolet (UV) light
- o Specialized training/expertise required
- o Consistency of material properties
- o Alkali attack
- o Possible moisture absorption
- o Tendency to creep
- o Possibility of FRP debonding or delaminating
- o Possibility of buckling / compression failure
- o Shortage of qualified suppliers
- o other:

5. Questions/Concerns

- Fire resistance
- Long term performance / short track record
- Performance at elevated temperatures
- Suitability in extreme cold
- Resistance to chemical spills
- Possible smoke toxicity
- Vandalism
- Inspectability
- Repairability
- Its non-ductile nature / possibility of brittle fracture
- Compatibility with other materials / strain compatibility
- Thermal properties
- Low E / stiffness
- Stray electrical current? (e.g. deck strengthened with carbon FRP)
- other:

If your agency is reluctant to use FRP, what could be done to alleviate concerns?

6. Design & Construction Procedures and Specifications

Who designed the FRP systems? FRP supplier / in-house staff / consultant

Do you have an in-house design manual for FRP systems?

What design specifications or guidelines were used?

Who provides installation procedures?

Do you use certification acceptance for the installed system?

Do you use FRP in salt water or harsh corrosive environment?

If you use FRP for external post-tensioning, and what types of anchoring system do you use?

7. Quality Assurance and Construction Process Control

Do your agency have a list of "approved suppliers" or "approved FRP systems"?

Does your agency allow use of FRP systems without site-specific approval?

Do you monitor the performance of FRP installations (other than biennial inspections)

Do you typically require laboratory tests of FRP materials?

Do you typically require laboratory tests of prototype components?

Do you require pre-construction training for field inspectors assigned to FRP applications?

Describe your quality (QA/QC) processes.

What acceptance criteria do you use for FRP strengthened structures?

Do you specify minimum qualifications for installers?

What items are required as part of a submittal package?

- Working Drawings
- Description of the proposed FRP system
- Design calculations
- Material safety data sheets (MSDS)
- Manufacturer's system data sheets (Mix ratio, Pot life, Temp. restrictions etc.)
- Material properties (mechanical, physical, and chemical) of all components of FRP system)
- Installation procedures
- Maintenance procedures
- Schedule

Appendix F: FRP Specialists

FRP Use	DOT Contact
E1. Repair of impact-damaged concrete (reinforced or prestressed)	William Potter, FDOT
E2. Repair of corrosion-damaged concrete	William Potter, FDOT
E3. Seismic retrofit of concrete	Caltrans
E4. Protective wrapping of concrete	–
E5. Strengthening concrete with externally bonded FRP	–
E6. Strengthening concrete with near-surface mounted (NSM) FRP	–
E7. Strengthening concrete with FRP post-tensioning	–
E8. Strengthening concrete with mechanically-fastened FRP	–
E9. Strengthening structural steel with FRP post-tensioning	–
E10. Culvert liner	–
E11. Repair of impact-damaged metal poles	William Potter, FDOT
E12. Repair of fatigue-damaged aluminum overhead sign structures	Rich Marchione, NYSDOT
E13. Repair and strengthening of timber	Donnie Williams, WVDOT
N1. Concrete reinforcement (reinforcement, dowels)	NDOR
N2. Concrete prestressing (pre-tensioning)	Steven Kahl, MDOT; William Potter, FDOT
N3. Concrete prestressing (post-tensioning)	Steven Kahl, MDOT
N4. Stay-in-place (SIP) concrete forms (decks, substructures)	–
N5. Superstructures – FRP beams and slabs	–
N6. Hybrid superstructure system – FRP beams and slabs	Wayne Frankhauser Jr., MaineDOT
N7. Hybrid superstructure system – concrete-filled FRP tubes	Wayne Frankhauser Jr., MaineDOT
N8. Hybrid superstructure system – FRP with glue-laminated lumber (glu-lam)	Wayne Frankhauser Jr., MaineDOT
N9. Structural deck, FRP, or hybrid	–
N10. Pedestrian bridges	–
N11. Sidewalks	–
N12. Bridge drains and scuppers	Stacy McMillan, MoDOT
N13. Load-bearing pile foundations, FRP or hybrid	William Potter, FDOT
N14. Marine fenders (piles, wales)	William Potter, FDOT
N15. Marine floats	Wayne Frankhauser Jr., MaineDOT
N16. Sheet piling	–
N17. Noise barrier	–
N18. Wind fairing	–
N19. Railing – bridge, guide, and guard	–
N20. Culverts	–
N21. Light, sign, or signal structures	–

Appendix G:
Case Studies and Additional Resources by State

Florida DOT

- Design Innovation, Office of Design – Design Innovation, Florida Department of Transportation, http://www.fdot.gov/design/innovation/
- Fiber Reinforced Polymer (FRP) Reinforcing Bars and Strands, Fiber-Reinforced Polymer Reinforcing, Structures Design – Transportation Innovation, Florida Department of Transportation, http://www.fdot.gov/structures/innovation/FRP.shtm
- Fiber-Reinforced Polymer Guidelines (FRPG), FDOT Structures Manual, Volume 4, January 2017, http://www.fdot.gov/structures/structuresmanual/currentrelease/vol4frpg.pdf
- Structures Research Center, Structures Design – Divisions, Florida Department of Transportation, http://www.fdot.gov/structures/StructuresResearchCenter/default.shtm

Maine DOT

Concrete-Filled Composite Arch

The original research project with the University of Maine's Advanced Engineered Wood Composites Center[87] (AEWC) resulted in the development and laboratory testing of the concrete-filled FRP arch tubes.

- Design, Construction and Testing of the Neal Bridge in Pittsfield, Maine, October 2009, http://ntl.bts.gov/lib/51000/51500/51536/design_construction_and_testing_of_the_Neal_Bridge_in_Pittsfield_Maine.pdf

A second research project examined and improved the system for longer span lengths, modeling of the unfilled tubes for construction loads, reduction of costs through design optimization, more-accurate soil-structure interaction, and material durability. A final task not completed yet is conducting monitoring and load testing on completed bridges.

- Technical Report 14-02: Bridge-in-a-Backpack™, Task 1: Investigation of Span Lengths Up to 70 Feet, August 2011, http://ntl.bts.gov/lib/54000/54000/54097/report1402ft1.pdf
- Technical Report 14-02: Bridge-in-a-Backpack™, Task 2: Reduction of Costs Through Design Modifications and Optimization, September 2011, http://ntl.bts.gov/lib/54000/54000/54089/1403.pdf
- Technical Report 14-02: Bridge-in-a-Backpack™, Task 3: Investigation of Durability Enhancements Relative to Abrasion from Ice and Other Sources, February 2013, http://ntl.bts.gov/lib/54000/54000/54087/fullreport1404ft3opttest.pdf

A third research project is nearing completion. Tasks include development of splicing details for the arches; investigation of alternative shapes, soil-structure interaction half-scale laboratory testing; developing improved concrete mixes, guidelines for construction quality assurance and long-term inspection, and maintenance, fire resistance, and hydraulic roughness coefficient.

- Technical Report 14-14: Splicing and Local Reinforcement of Concrete Filled FRP Tubes, January 2014, http://ntl.bts.gov/lib/54000/54600/54696/1414techreport.pdf
- Technical Report 14-15: Manning's Roughness Coefficient for Buried Composite Arch Bridges, August 2014, http://ntl.bts.gov/lib/54000/54500/54555/report1415t.pdf
- Technical Report 15-01: Bridge-in-a-Backpack™, Task 4: Monitoring and Load Rating, January 2015, http://ntl.bts.gov/lib/55000/55300/55317/report1501f.pdf

87 Advanced Structures & Composites Center, University of Maine, https://composites.umaine.edu/

- Technical Report 15-02: Bridge-in-a-Backpack™, Tasks 2.1 and 2.2: Investigate Alternative Shapes with Varying Radii, February 2015, http://ntl.bts.gov/lib/55000/55300/55318/report1502f.pdf
- Technical Report 15-03: Bridge-in-a-Backpack™, Task 2.3: Low-Rise Arch Study with Soil-Structure Interaction and Spread Footing Foundation, January 2015, http://ntl.bts.gov/lib/55000/55300/55319/report1503f.pdf
- Technical Report 15-04: Bridge-in-a-Backpack™, Task 8: Investigation of Bridge Performance Under Extreme Temperatures, December 2014, http://ntl.bts.gov/lib/55000/55300/55320/report1504f.pdf
- Technical Report 15-05: Bridge-in-a-Backpack™, Task 7: Investigation of Damage and Repairs for Concrete Filled FRP Tubular Arches, April 2015, http://ntl.bts.gov/lib/55000/55300/55321/report1505f.pdf
- Technical Report 16-02: Bridge-in-a-Backpack™, Task 3.1: Investigate Soil-Structure Interaction—Experimental Design, January 2016, http://www.maine.gov/mdot/tr/docs/report1602f.pdf
- Technical Report 16-03: Bridge-in-a-Backpack™, Task 3.2: Investigate Soil-Structure Interaction—Modeling and Experimental Results of Steel Arches, January 2016, http://www.maine.gov/mdot/tr/docs/report1603f.pdf
- Technical Report 16-04: Bridge-in-a-Backpack™, Task 3.3: Investigate Soil-Structure Interaction—Modeling and Experimental Results of Concrete Filled FRP Tube Arches, January 2016, http://ntl.bts.gov/lib/60000/60300/60368/report1604f.pdf
- **Pittsfield, Neal Bridge** – 2008 – 28'-0" span, mass concrete abutment, 23 carbon fiber tubes @ 2'-0"spacing, composite decking with composite sheet pile headwall
- **Anson, Maine** (town-owned bridge) – 2009 – 27'-7" span, 9 carbon fiber tubes @ 3'-0" spacing, composite decking and corrugated composite panels with geo-grid mechanically stabilized earth
- **Auburn, Royal River** – 2010 – 38'-0" span, concrete abutment on sheet pile, 13 carbon fiber tubes @ 3'-1"spacing, composite decking with reinforced concrete deck, cast-in-place concrete and precast modular gravity wall
- **Belfast, Perkins Bridge** – 2010 – 47'-7" span, reinforced concrete footings and abutments on ledge, 16 carbon fiber tubes @ 2'-11" spacing, composite decking with reinforced concrete deck, cast-in-place concrete and precast modular gravity wall
- **Bradley, Jenkins Bridge** – 2010 – 28'-6" span, 19° skewed bridge, concrete abutment on sheet pile, 12 carbon fiber tubes @ 2'-11"spacing, composite decking with reinforced concrete deck, composite headwall panels attached with composite bolts and steel whaler
- **Caribou, Farm Access Underpass** – 2011 – 54'-2" span, mass reinforced concrete abutment, 22 carbon fiber tubes @ 2'-8" spacing, composite decking, reinforced concrete deck, cast-in-place headwall block with mechanically stabilized earth retaining wall with inextensible reinforcement straps and precast concrete facing panels, design/build contracting
- **LaGrange, B&A Overhead Bridge** – 2012 – 36'-1½" span, 55° skewed bridge, reinforced concrete spread footings and abutments, 13 carbon fiber tubes @ 9'-3/8" spacing, composite (guardrail) decking with reinforced shotcrete deck, cast-in-place concrete headwall and precast modular gravity wingwalls, staged construction
- **Ellsworth, Greys Brook Bridge** – 2013 – 34'-4" span, concrete abutment on sheet pile, 11 carbon

fiber tubes @ 4'-6" and 5'0" spacing, composite decking with reinforced concrete deck, cast-in-place concrete, and precast modular gravity wall

- **Edmunds Twp., Tide Mill 2 Bridge** – 2015 – 56'-0" span, reinforced concrete spread footings and abutments, 13 carbon fiber tubes @ 4'-2½" spacing, composite decking, cast-in-place grout with Redi-Rock[88] retaining wall, detail/build contracting

HC Beam

- **Boothbay, Knickerbocker Bridge** – 2011 – 540' eight-span bridge over saltwater, max span length 70', 32' bridge width with eight 2'9" deep beams.
  Project included laboratory testing a 70' beam at the AEWC. Testing results validated the design procedure results.
- Bangor, **Union Street Bridge** – 2016 – 184' two-span overpass, max span length 92', 74' bridge width with seven double-stem 3'9" deep HC beams
- **Westbrook, Bridge Street Bridge** – 2016 – 160' two-span structure, max span length 80', 35'4" bridge width with seven 36' deep HC beams, stay-in-place FRP deck panels
- **Thomaston, Wadsworth Bridge** – 2017 – 280' four-span bridge over saltwater, max span length 70.75', 36' bridge width with six 2'9" HC beams, partial depth precast concrete deck panels

GFRP Reinforcement

MaineDOT has used GFRP in four bridge decks since 2013 and currently has several more in design.

FRP Strengthening

The University of Maine (UMaine) AEWC has developed an FRP strengthening system for concrete slabs and beams as part of the Advanced Bridge Safety Initiative. The system has not yet been implemented on bridges.

- Technical Report 14-08: Advanced Bridge Safety Initiative, FRP Flexural Retrofit for Concrete Slab Bridges—Task 4: Deliverables, June 2014, http://ntl.bts.gov/lib/54000/54000/54098/report1408ftestone.pdf

Carbon Fiber

- **Prospect – Verona, Penobscot Narrows Bridge** – As part of the Penobscot Narrows Bridge construction six CFCC strands were installed in six different stays. The strands are being monitored by AEWC for long-term performance.
  - Rohleder W, et al., Carbon Fiber-Reinforced Polymer Strand Application on Cable-Stayed Bridge, Penobscot Narrows, Maine, Transportation Research Record, Vol 2050, Transportation Research Board, The National Academies of Sciences, Engineering, and Medicine http://trrjournalonline.trb.org/doi/10.3141/2050-17
  - Technical Report 15-10: Long-Term Monitoring of Carbon Composite Strands in the Penobscot-Narrows Bridge, June 2015, http://ntl.bts.gov/lib/55000/55300/55363/report1510f__1_.pdf
- **Fryeburg CFCC post-tensioning** – 2012 – CFCC strands were used for post-tensioning of the precast voided slab beams.

88 Redi-Rock, Redi-Rock International, https://www.redi-rock.com/

Technical Report 13-02: Post-Tensioned Carbon Fiber Composite Cable (CFCC), Little Pond Bridge, Route 302, Fryeburg, Maine, February 2013, http://ntl.bts.gov/lib/51000/51500/51553/Post-tensioned_carbon_fiber_composite_cable_cfcc.pdf

- **Kittery, Overpass Bridge** – 2014 – CFCC prestressing strand used for precast, prestressed NEXT – D beams, 60' span with 75'4" fascia to fascia width, beams fabricated by High Concrete Group[89]

FRP Piles

- Technical Report 12-05: Fiber-Reinforced Polymer (FRP) Composite Piles Used on Pier Rehabilitation, Little Diamond Island, Casco Bay, Portland, Maine, October 2012
- Richmond-Dresden – UMaine AEWC investigating the use of FRP piles for bridges. Tasks are driving test piles at the Richmond-Dresden Bridge project, laboratory testing of hollow and concrete-filled piles, durability testing, and development of draft geotechnical and structural design specifications.
    - Technical Document 15-06: Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles, Task 1: Mechanical Properties of FRP Piles, October 2015, http://ntl.bts.gov/lib/55000/55300/55322/report1506f.pdf
    - Technical Document 15-07: Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles, Task 2: FRP Composite Pile Driving at the Richmond-Dresden Bridge Over the Kennebec River, January 2014, http://ntl.bts.gov/lib/55000/55300/55323/report1507f__2_.pdf
    - Technical Report 15-08: Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles, Task 3: FRP Composite Pile Flexural Testing, June 2014, http://ntl.bts.gov/lib/55000/55300/55324/report1508f.pdf
    - Technical Report 15-09: Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles, Task 6: FRP Composite Pile Axial Compression Testing, April 2015, http://ntl.bts.gov/lib/55000/55300/55362/report1509f__1_.pdf

FRP Bridge Drain

UMaine AEWC and Kenway designed, tested, and manufactured bridge drains that were installed bridge maintenance forces on three MaineDOT bridges. Since then numerous other bridges have used FRP bridge drains with similar dimensions to our standard bridge steel drain details. The New England Transportation Consortium (a research cooperative between Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) is developing standard FRP bridge drain details and specifications and conducting testing to certify that manufacturer's drains will meet specifications. MaineDOT has installed FRP drains on approximately 10 bridges in the past five years.

Amherst FRP Culvert Lining and Others

Installed on three pipe culvert invert lining projects to date
Technical Report 10-03: Culvert Rehabilitation and Invert Lining Using Fiber-Reinforced Polymer (FRP) Composites, June 2010, http://ntl.bts.gov/lib/51000/51500/51535/Culvert_invert_lining_with_fiber_reinforced.pdf

89 High Concrete Group, LLC, http://www.highconcrete.com/

Michigan DOT

Research reports (newest to oldest):

- Design and Construction Guidelines for Strengthening Bridges Using Fiber-Reinforced Polymers (FRP), September 2014, http://www.michigan.gov/documents/mdot/RC1614_474895_7.pdf
- Improved Shallow Depth Patches for Concrete Structures, February 2008, http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1502_228600_7.pdf
- Sensors to Monitor Bond in Concrete Bridges Rehabilitated with FRP, October 2003, http://www.michigan.gov/documents/mdot_rc-1435_80428_7.pdf
- Repair of Corrosion-Damaged Columns Using FRP Wraps, December 2000, http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1386_324520_7.pdf
- Repair and Strengthening of Reinforced Concrete Beams Using CFRP Laminates, Task 9: Computer Program, June 2000, http://www.michigan.gov/documents/mdot/MDOT_RC-1382_412158_7.pdf
- Glued-On Fiber Reinforced-Plastic (FRP) Sheets for Repair and Rehabilitation: Summary of Current State of Knowledge, August 1997, http://www.michigan.gov/documents/mdot/MDOT_RC-1355_412402_7.pdf

MDOT previously approved special provisions (see http://mdotjboss.state.mi.us/SpecProv/specProvHome.htm). To download these documents, select the Special Provision category "2012 Previously Approved" from the drop-down menu about half-way down the page.

- Division 7 – Structures
    - Carbon Fiber Composite Cables Transverse Post-Tensioning - 12DS708(A255)
    - Column Wrapping With Fiber Reinforced Polymer Sheets-12CT712(A135)
- Division 8 – Incidental Construction
    - Carbon Fiber Composite Cable Reinforcement Delivery-12DS800(I600)
    - Carbon Fiber Composite Cables Anchoring Device-12DS800(D195)
    - Fiber Reinforced Plastic Grating-12DS800(K880)
    - Field Installation of Carbon Fiber Composite Cable Reinforcement-12DS800(D475)

Appendix H: Sample Bid Prices for FRP Items

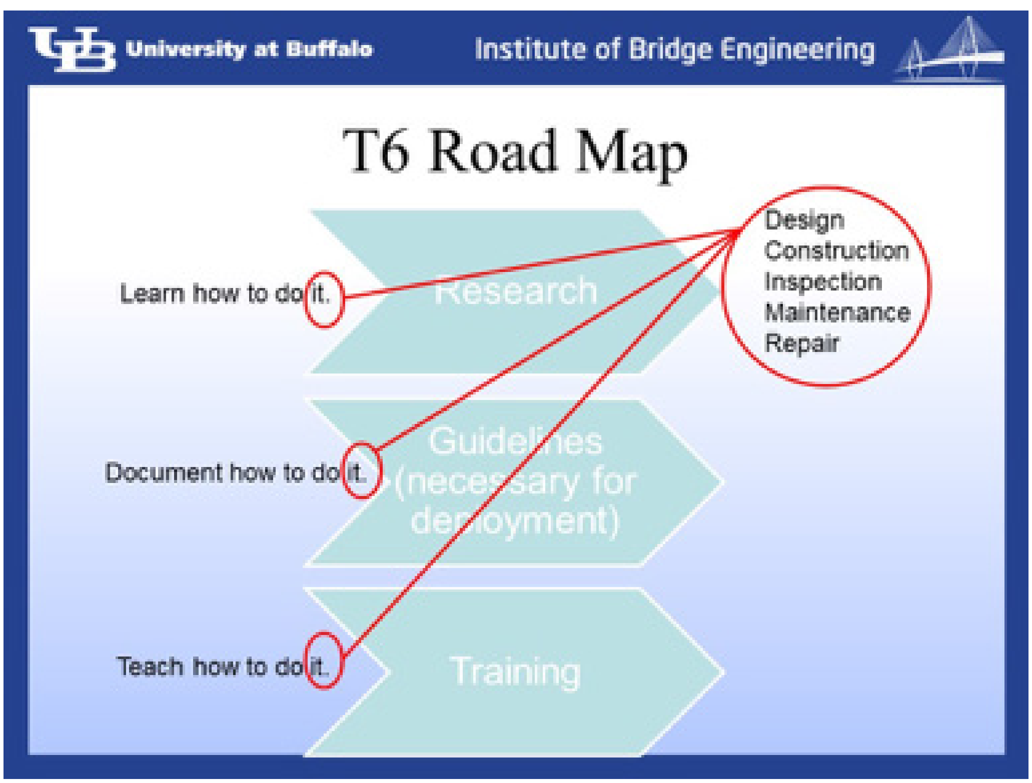
The following table is a summary of actual bid data from MDOT.

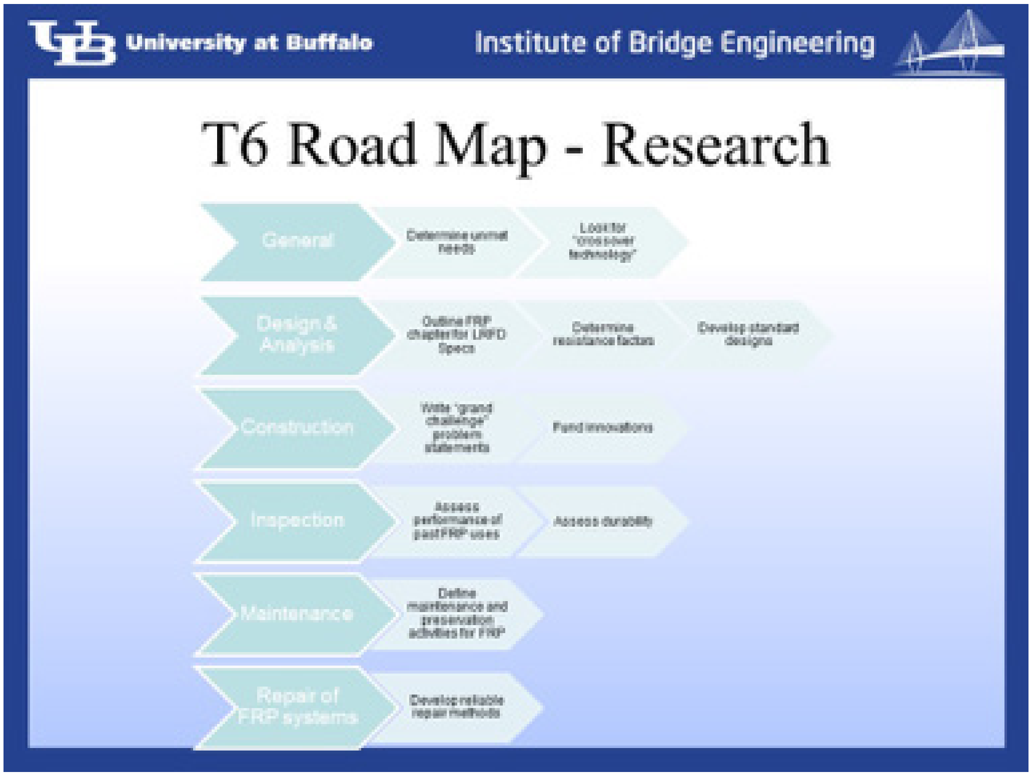
Weighted Average Bid Prices for FRP Items

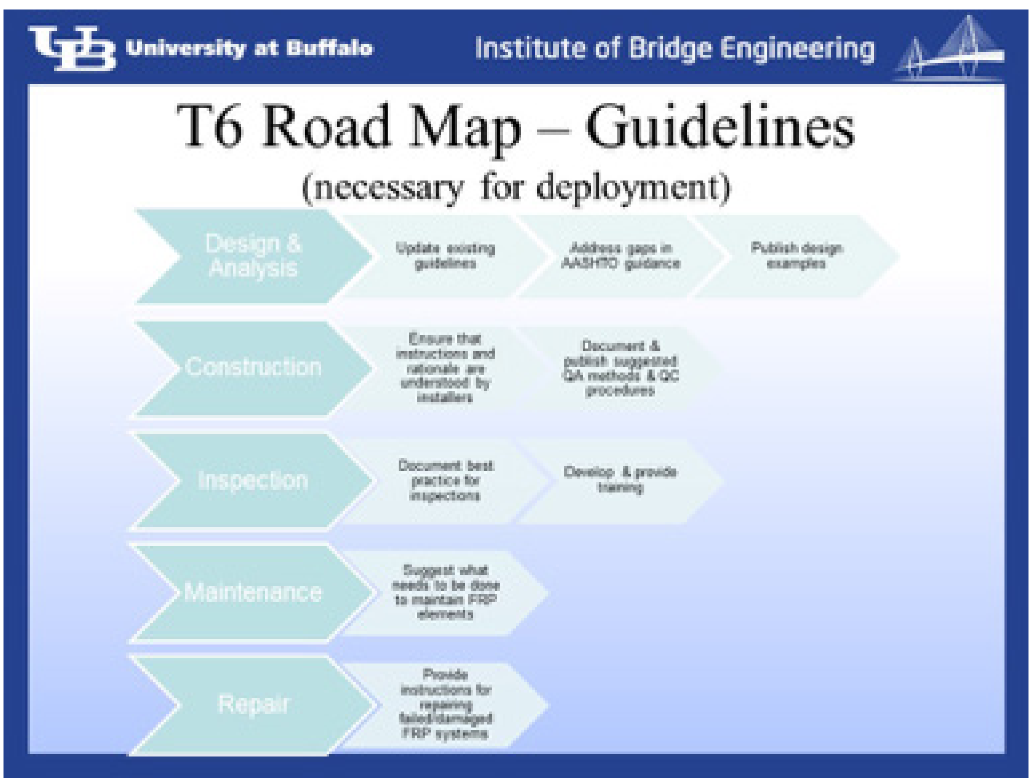
Item Description	Units	Calendar Qtr	Num of Conts	Total Qty	Total Dollars	Avg Award Price	Avg Low 3 Bidders
_CFCC Post Tensioning, Furnish (S09 of 82193)	LSUM	2010Q3	1	1	$5,350	$5,350	$43,388
_Composite Arch Superstructure, Install 12 inch (C19 of 32092)	LSUM	2010Q1	1	1	$45,000	$45,000	$170,084
_Composite Arches, Furn, 12 inch (C19 of 32092)	LSUM	2012Q1	1	1	$285,000	$285,000	$170,084
_CFCC Post Tensioning, Furnish (R01 of 38072)	LSUM	2012Q1	1	1	$210,000	$210,000	$187,583
_Post Tensioning, CFCC (R01 of 38972)	LSUM	2012Q1	1	1	$365,000	$365,000	$187,583
_CFCC Post Tensioning, Furnish (S18-3 of 77111)	LSUM	2013Q3	1	1	$210,000	$210,000	$272,864
_CFCC Post Tensioning, Furnish (S18-4 of 77111)	LSUM	2013Q3	1	1	$210,000	$210,000	$272,864
_Post Tensioning, CFCC (S18-3 of 77111)	LSUM	2013Q3	1	1	$175,000	$175,000	$272,864
_Post Tensioning, CFCC (S18-4 of 77111)	LSUM	2013Q3	1	1	$175,000	$175,000	$272,864
_Column Wrap with FRP Sheet	Sft	2008Q3	1	216	$18,360	$85	$92
_Column Wrap with FRP Sheet	Sft	2010Q1	1	49000	$1,323,000	$27	$28
_Fiber Wrap Repair	Sft	2010Q3	1	71	$5,112	$72	$84
_Concrete Wrap FRP Sheet	Sft	2011Q2	1	800	$33,440	$42	$36
_Shear Strengthening Sys. w/FRP Sheet	Sft	2011Q4	1	1195	$60,348	$51	$48
_Column Wrap with FRP Sheet	Sft	2011Q4	1	3105	$91,939	$30	$34
_Shear Strengthening Sys. w/FRP Sheet	Sft	2013Q1	1	6335	$127,334	$20	$20
_Column Wrap with FRP Sheet	Sft	2013Q2	2	1710	$30,541	$18	$21
_Column Wrap with FRP Sheet	Sft	2013Q3	1	120	$4,500	$38	$38
_Column Wrap with FRP Sheet	Sft	2015Q1	1	2604	$26,040	$10	$3,653
_Column Wrap with FRP Sheet	Sft	2015Q3	1	2604	$49,971	$19	$24
_CFCC Reinforcement, Furnish	Ft	2013Q1	1	208328	$1,041,640	$5.00	$4.04
_CFCC Reinforcement, Install	Ft	2013Q1	1	72493	$50,745	$0.70	$4.04
_Column Repair	Ft	2015Q1	1	200	$200	$1	$1
_Column Repair	Ft	2015Q2	1	320	$16,000	$50	$61
CFCC = Carbon Fiber Composite Cables							

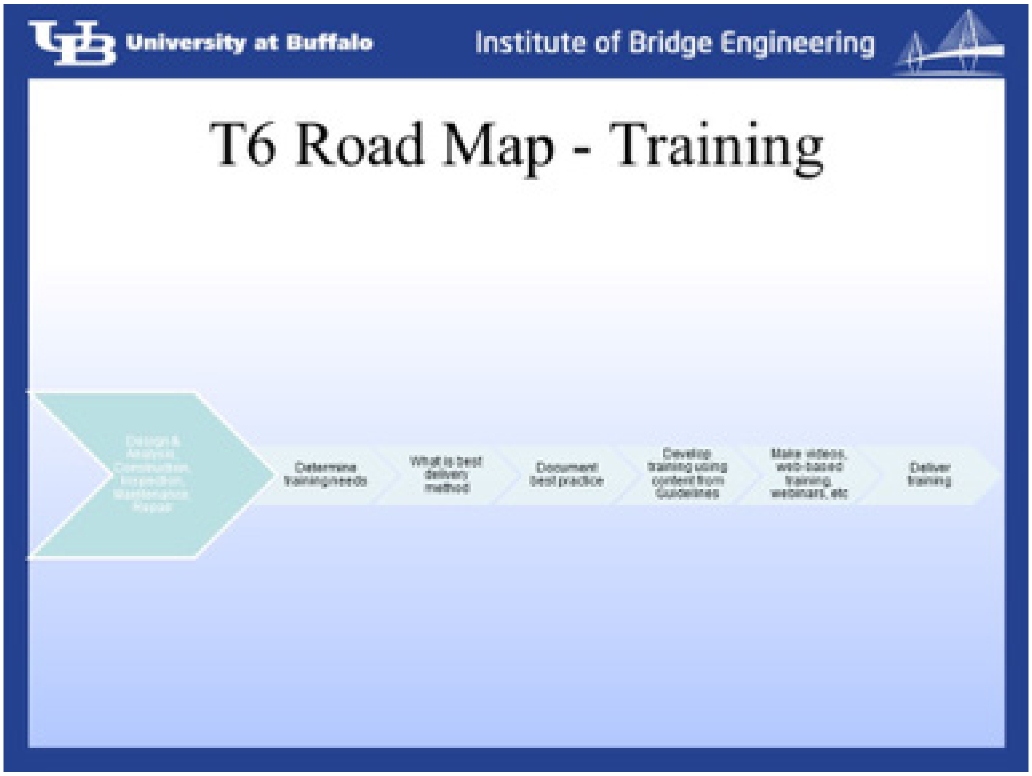
Appendix I: Preliminary T6 Road Map

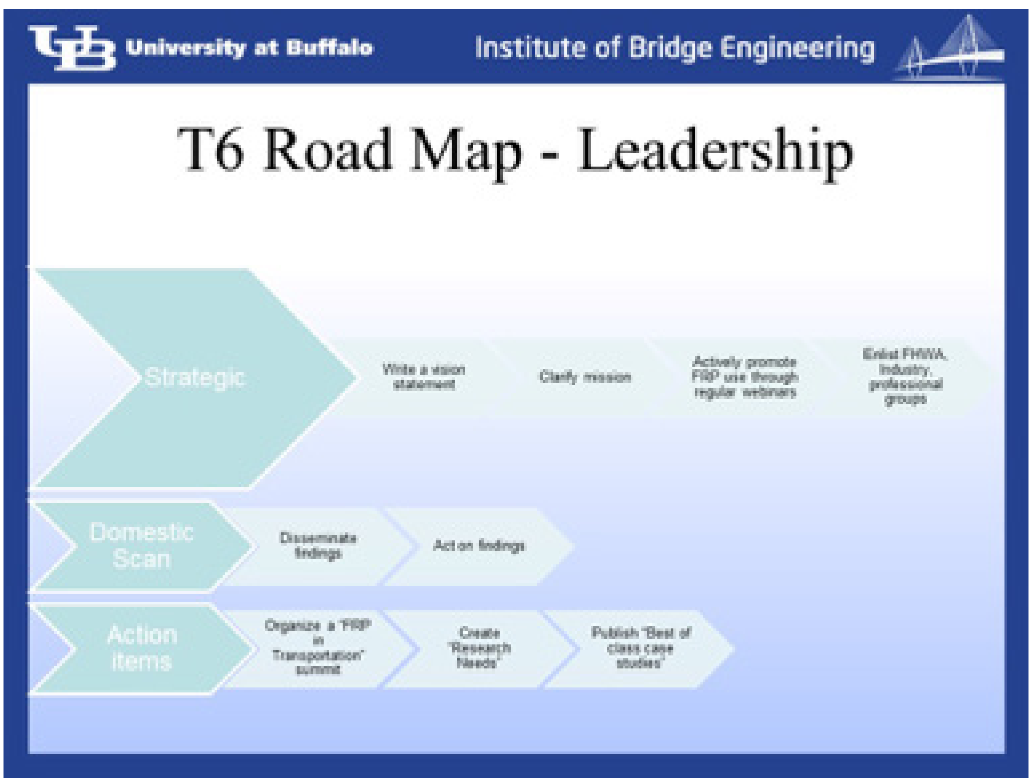

University at Buffalo
Institute of Bridge Engineering
T6 Road Map
Learn how to do it.
Research
Document how to do it.
Guidelines (necessary for deployment)
Teach how to do it.
Training


University at Buffalo
Institute of Bridge Engineering
T6 Road Map
Design
Construction
Inspection
Maintenance
Repair
Learn how to do it.
Research
Document how to do it.
Guidelines (necessary for deployment)
Teach how to do it.
Training


University at Buffalo
Institute of Bridge Engineering
T6 Road Map - Research
General
Determine unmet needs
Look for "crossover technology"
Design & Analysis
Outline FRP chapter for LRFD Specs
Determine resistance factors
Develop standard designs
Construction
Write "grand challenge" problem statements
Fund innovations
Inspection
Assess performance of past FRP uses
Assess durability
Maintenance
Define maintenance and preservation activities for FRP
Repair of FRP systems
Develop reliable repair methods


University at Buffalo
Institute of Bridge Engineering
T6 Road Map – Guidelines
(necessary for deployment)
Design & Analysis
Update existing guidelines
Address gaps in AASHTO guidance
Publish design examples
Construction
Ensure that instructions and rationale are understood by installers
Document & publish suggested QA methods & QC procedures
Inspection
Document best practice for inspections
Develop & provide training
Maintenance
Suggest what needs to be done to maintain FRP elements
Repair
Provide instructions for repairing failed/damaged FRP systems


University at Buffalo
Institute of Bridge Engineering
T6 Road Map - Training
Design & Analysis, Construction, Inspection, Maintenance Repair
Determine trainingneeds
What is best delivery method
Document best practice
Develop training using content from Guidelines
Make videos, web-based training, webinars, etc
Deliver training


University at Buffalo
Institute of Bridge Engineering
T6 Road Map - Leadership
Strategic
Write a vision statement
Clarify mission
Actively promote FRP use through regular webinars
Enlist FHWA, Industry, professional groups
Domestic Scan
Disseminate findings
Act on findings
Action items
Organize a "FRP in Transportation" summit
Create "Research Needs"
Publish "Best of class case studies"

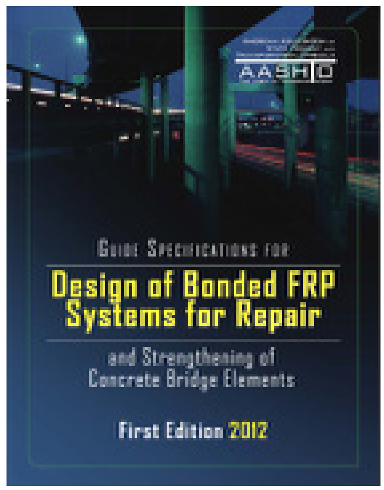
Appendix J: Bibliography

Technology Readiness Assessment (TRA) Guidance, US Department of Defense, Assistant Secretary of Defense for Research and Engineering, 2011 (revised May 2011), http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf

American Association of State Highway and Transportation Planning Officials (AASHTO) Guidelines

AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, 1st Edition, 2009, https://bookstore.transportation.org/Item_details.aspx?id=1545
Errata to above document, July 2013, http://downloads.transportation.org/GFRP-1-E1.pdf

Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge



Elements, 1st Edition, 2012, https://bookstore.transportation.org/collection_detail.aspx?ID=118

Guide Specifications for Design of FRP Pedestrian Bridges, 1st Edition, 2008, https://bookstore.transportation.org/item_details.aspx?id=1218

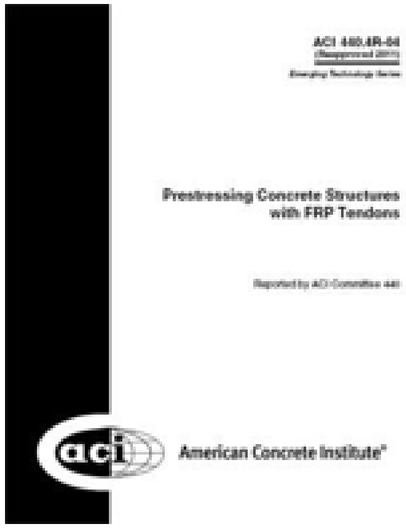
AASHTO LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes, 1st Edition, 2012, https://bookstore.transportation.org/collection_detail.aspx?ID=119

American Concrete Institute (ACI) Guidelines

440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars, 2015, https://www.concrete.org/store/productdetail.aspx?ItemID=440115

440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, 2008, https://www.concrete.org/store/productdetail.aspx?ItemID=440208

440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures, 2012, https://www.concrete.org/store/productdetail.aspx?ItemID=440312



440.4R-04: Prestressing Concrete Structures with FRP Tendons (Reapproved 2011), 2004, https://www.concrete.org/store/productdetail.aspx?ItemID=440404

440.5-08 Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars, 2008, https://www.concrete.org/store/productdetail.aspx?ItemID=440508&Format=DOWNLOAD

440.5M-08 Metric Specification for Construction with Fiber-Reinforced Polymer (FRP) Reinforcing Bars, 2008, https://www.concrete.org/store/productdetail.aspx?ItemID=4405M08&Format=DOWNLOAD

440.6-08 Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement, 2008, https://www.concrete.org/store/productdetail.aspx?ItemID=440608

440.6M-08 Metric Specification for Carbon & Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement, 2008, https://www.concrete.org/store/productdetail.aspx?ItemID=4406M08

440.7R-10 Guide for Design & Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures, 2010, https://www.concrete.org/store/productdetail.aspx?ItemID=440710&Format=DOWNLOAD

440.8-13 Specification for Carbon and Glass Fiber-Reinforced Polymer Materials Made by Wet Layup

for External Strengthening of Concrete and Masonry Structures, 2014, https://www.concrete.org/store/productdetail.aspx?ItemID=440813

440.8M-13 Metric Specification for Carbon and Glass Fiber-Reinforced Polymer Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures, 2014, https://www.concrete.org/store/productdetail.aspx?ItemID=4408M13

440.9R-15 Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforced Polymer (FRP) Reinforcement, 2015, https://www.concrete.org/store/productdetail.aspx?ItemID=440915

440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, 2007, https://www.concrete.org/store/productdetail.aspx?ItemID=44007&Format=DOWNLOAD

562M-13 Metric Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete (ACI 562-13) & Commentary, 2013, https://www.concrete.org/store/productdetail.aspx?ItemID=562M13

American Composite Manufacturers' Association (ACMA)

ACMA maintains a list of transportation infrastructure projects that have utilized FRP materials[90]. Note that the list excludes repair or strengthening projects, which are thought to be numbered in the thousands.

For information, contact:

John P. Busel, FACI
Vice President, Composites Growth Initiative
American Composites Manufacturers Association
Phone: 914-961-8007
E-mail: jbusel@acmanet.org
Website: www.compositesinfrastructure.org

American Society for Testing and Materials (ASTM) Test Methods for FRP

The following ASTM technical committees are actively working to gain consensus on test methods for FRP rebar, repair materials, and pultruded structural profiles.

- ASTM D20.18.01, FRP Materials for Concrete, is addressing materials and products to develop standard test methods for FRP rebar and repair materials.
- ASTM D20.18.02, Pultruded Profiles, is focused on the development of test methods for FRP pultruded profiles and shapes.
- ASTM D30.30.01, Composites for Civil Engineering, is addressing FRP composites products used construction.

Some tests that are used for FRP specimens are:

- ASTM D1761, Standard Test Methods for Mechanical Fasteners in Wood
- ASTM D1894, Coefficient of Friction

90 Installations, Transportation Infrastructure, FRP Composites, Transportation Structures Council of the American Composites Manufacturers Association, http://www.compositesinfrastructure.org/installations/

- ASTM D2240, Standard Test Method for Rubber Property—Durometer Hardness
- ASTM D2583, Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
- ASTM D4060, Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser
- ASTM D543, Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents
- ASTM D570, Standard Test Method for Water Absorption of Plastics
- ASTM D6109, 13 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastic Lumber and Related Products
- ASTM D638, Standard Test Method for Tensile Properties of Plastics
- ASTM D695, Standard Test Method for Compressive Properties of Rigid Plastics
- ASTM D7337, Standard Test Method for Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars
- ASTM D746, Test Method for Brittleness Temperature of Plastics and Elastomers by Impact
- ASTM D7522, Standard Test Method for Pull-Off Strength for FRP Laminate Systems Bonded to Concrete Substrate
- ASTM D790, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
- ASTM D792, Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
- ASTM E84, Standard Test Method for Surface Burning Characteristics of Building Materials
- ASTM G154, Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials

National Highway Institute (NHI) Web-Based Training

Introduction to FRP Materials and Applications for Concrete Structures, http://www.nhi.fhwa.dot.gov/training/course_search.aspx?tab=0&key=FRP&sf=0&course_no=130105A

Construction Procedures and Specifications for Bonded Repair and Retrofit of Concrete Structures, http://www.nhi.fhwa.dot.gov/training/course_search.aspx?tab=0&key=FRP&sf=0&course_no=130105B

Quality Control of Repair and Retrofit of Concrete Structures Using FRP Composites, http://www.nhi.fhwa.dot.gov/training/course_search.aspx?tab=0&key=FRP&sf=0&course_no=130105C

National Cooperative Highway Research Program (NCHRP) Research Reports

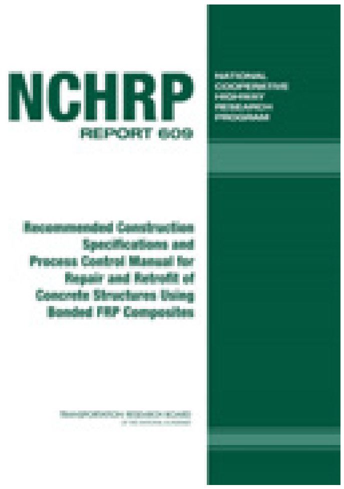
NCHRP Report 503, Application of Fiber Reinforced Polymer Composites to the Highway Infrastructure, 2003, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_503.pdf

NCHRP Report 514, Bonded Repair and Retrofit of Concrete Structures Using FRP Composites:

Recommended Construction Specifications and Process Control Manual, 2004, (superseded by NCHRP Report 609), http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_514s1.pdf

NCHRP Report 564, Field Inspection of In-Service FRP Bridge Decks, 2006, https://www.nap.edu/login.php?record_id=23284&page=https%3A%2F%2Fwww.nap.edu%2Fdownload%2F23284

Field Inspection of In-Service FRP Bridge Decks (2006) http://www.trb.org/Publications/Blurbs/156715.aspx



NCHRP Report 609, Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites, 2008, http://www.trb.org/Publications/Blurbs/159694.aspx

NCHRP Report 655, Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 2010, http://www.trb.org/Publications/Blurbs/163871.aspx

NCHRP Report 678, Design of FRP Systems for Strengthening Concrete Girders in Shear, 2011, http://www.trb.org/Publications/Blurbs/164622.aspx

Select Research Reports Since 1998, Alphabetical by Author

See file entitled “FRP Bibliography.pdf”

Appendix K: Thermoplastics in Transportation Infrastructure

The information and images in this section were provided by John S. Kim, PhD, PE, Michael Baker International[91].

Figure K1 Thermoplastic beams

Figure K2 Thermoplastic decking

91 Michael Baker International, http://www.mbakerintl.com/

Figure K3 Completed thermoplastic bridge in Ohio, opened in 201

Chandra V, J Kim, TJ Nosker, and G Nagle, World's First Thermoplastic Bridges, Proceedings of FHWA Bridge Engineering Conference, Orlando, FL, April 2010

Fan B and GE Novak, Creep Prediction for Polymer: Implementation and its Application on a Talc Filled Polypropylene, in Proceedings, Society of Plastics Engineers 2006 ANTEC Conference, Society of Plastics Engineers, Charlotte, NC, 2006

Kim J, V Chandra, and TJ Nosker, Sustainable Bridge Solutions Using Recycled Plastics, Proceedings of International Bridge Conference, Pittsburgh, PA, 2011

Lynch JK, TJ Nosker, and RW Renfree, Creep Prediction Using The Non-Linear Strain Energy Equivalence Theory, SPE-ANTEC Technical Papers, 2004

Lynch JK, TJ Nosker, and RW Renfree, Polystyrene/Polyethylene Composite Structural Materials, Vol. 1, The Center of Advanced Materials via Immiscible Polymer Processing, 2002