Report on Techniques for Bridge Strengthening

Main Report

April 2019

U.S. Department of Transportation
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Foreword

Over the service life of a highway bridge, its constituent materials are continually subjected to deterioration from mechanical loads, and chemical and environmental stressors. Heavy trucks, operational safety treatments (deicing chemicals) and aggressive environments frequently cause a degradation of capacity over time. In addition, legal truck weights as well as traffic volumes on the nation’s highway bridges are growing which might create demands in excess of those considered during their original design. As a result, there are many scenarios where it has become necessary to strengthen an existing structure to restore capacity or add capacity for a bridge to remain open to legal and unrestricted loads. Several of the structural retrofit and strengthening techniques available to restore or add capacity to a bridge through rehabilitation or reconstruction include concrete jacketing, steel plate bonding, FRP strengthening, and external post-tensioning.

This report is the first in a series of five that will provide information on new or emerging bridge strengthening methods for bridge owners and bridge engineers. This first report provides an overview of the topic and introduces a variety of strengthening techniques with a primary focus on the use of fiber reinforced polymer (FRP) composites. The remaining reports will each detail a design application to aid in a bridge strengthening retrofit using one of the technologies introduced in this report.

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16. Abstract Over the last two decades, new methods of strengthening bridges using both traditional materials and fiber-reinforced polymer (FRP) composites have been developed in an effort to meet the increasing demands applied on the aging and deteriorating transportation system by present day traffic. This report provides information for bridge owners and bridge engineers regarding these new and emerging bridge strengthening methods. This report provides a summary of the findings of Task 6: Report on Techniques for Bridge Strengthening, one task performed under Project Award: DTFH61-11-H-00027: Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ABS	Acrylonitrile Butadiene Styrene
ACM	Advanced Composite Materials
ACI	American Concrete Institute
AFRP	Aramid Fiber Reinforced Polymer
AISC	American Institute for Steel Construction
AISI	American Iron and Steel Institute
BMC	Bulk Molding Compounds
CFRP	Carbon Fiber Reinforced Polymer
CVD	Chemical Vapor Deposition
DGEBA	Diglycidyl Ether of Bisphenol-A
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FRCM	Fiber Reinforced Cementitious Matrix
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
GMT	Glass Mat Thermoplastic
IBRC	Innovative Bridge Research & Construction
IBRD	Innovative Bridge Research & Deployment
KYTC	Kentucky Transportation Cabinet
LRFD	Load and Resistance Factor Design
MDOT	Michigan Department of Transportation
MF	Mechanically Fastened
NCHRP	National Cooperative Highway Research Program
NSM	Near Surface Mounted
NYDOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation
PAF	Powder Actuated Fastened
PAN	Polyacrylonitrile
PEEK	Polyether-Ether Ketone
PPD-T	Poly-Paraphenylene-Diamine-Terephthalamide
PVC	Polyvinyl Chloride
RTM	Resin Transfer Molding
SFRP	Spray Fiber Reinforced Polymer

SMC	Sheet Molding Compounds
TRB	Transportation Research Board
TSP	Technical Services Program
UD	Unidirectional
UHPC	Ultra-High Performance Concrete
UV	Ultra-violate
VARTM	Vacuum-Assisted Resin Transfer Molding
VDOT	Virginia Department of Transportation
WSDOT	Washington State Department of Transportation

CHAPTER 1. INTRODUCTION

The purpose for this report and its contents are described in the following sections.

1.1 Purpose of Report

The nation's population and economy are growing, which puts larger stresses on our aging and deteriorating infrastructure. The aging transportation system needs to be upgraded to support the increase in demand. As a result, bridge owners and bridge engineers are looking for efficient and economical methods to repair their bridges and increase their live load capacity. These methods need to be cost effective and constructible, and they need to yield solutions that will lengthen the service life of the structure.

Over the last two decades, new methods of strengthening bridges have been developed in an effort to meet the increasing demands placed on the aging infrastructure by present day traffic. Traditional methods of strengthening have been described in detail in NCHRP project and synthesis reports conducted in 1997 and 1987.(1,2) This report focuses on new methods and variations of traditional methods developed since the 1997 report. During this time, the vast majority of new innovations in the field of bridge strengthening have involved applications of fiber reinforced composite materials.

The purpose of this report is to make information on these new and emerging technologies more readily available to bridge owners and bridge engineers. This report provides a summary of the findings of Task 6: Report on Techniques for Bridge Strengthening, one task performed under Project Award: DTFH61-11-H-00027: Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance. Additional information regarding the work can be found in the master's thesis of Tiera Rollins.(3)

1.2 Contents of Report

The following is an outline of the report. Because a basic understanding of advanced composites is fundamental to the remained of the work, Chapter 2 presents an overview of fiber-reinforced composite materials including fibers, resins, and the manufacturing process. Chapter 3 discusses bridge strengthening methods by first providing a summary of the prior synthesis reports (which present strengthening methods using traditional materials), as well as providing a summary of emerging methods. Chapter 4 covers national specifications for both traditional and composite material applications, while Chapter 5 discusses specific design criteria and specifications that have been developed for composite material applications. Chapter 6 presents an overview of construction and material specifications for composite material applications. Chapter 7 provides a summary of field applications of bridge strengthening techniques using composite materials. Chapter 8 discusses the four bridge strengthening examples that were developed (all involving traditional materials), as well as three existing examples that illustrate the use of composite materials. Finally, Chapter 9 provides a summary of the project and recommendations for future work.

CHAPTER 2. COMPOSITE MATERIAL OVERVIEW

A composite material consists of two or more constituent materials that have distinct physical and/or chemical properties. For instance, two-phase metal alloys are particulate composites in terms of different atomic structures.(4) Basically, the combination of the selected constituent materials creates a material with enhanced properties and targeted performance goals. Within a composite material, one or more discontinuous constituents are fully embedded in a continuous constituent material.(5) The discontinuous constituents are usually stronger than the continuous constituent and act as the load carrying structural phase, i.e., the reinforcement or reinforcing material in forms of fibers, particles, flakes, etc.(6) The continuous constituent is the body phase that encompasses the entire structural phase and is termed the matrix.(4-6)

2.1 What is an FRP Composite Material?

Fiber reinforced polymers (FRP, also called fiber reinforced plastics) are a good example of a composite material. FRPs consist of a thermosetting or thermoplastic polymer matrix and embedded reinforcing fibers.(4-6) The fibers are fabricated filaments with diameters in micron scale and can be in the form of short, long, continuous and discontinuous fibers. For instance, figure 1 schematically shows a unidirectional composite in which long and continuous fibers are distributed homogeneously along the longitudinal direction (i.e., fiber direction) and randomly throughout the cross section of the composite. In FRPs, the fiber network is the load-carrying component of the composite and the matrix serves to bond the fibers together, transfer loads to the fibers, maintain fiber orientations, and provide protection to the fibers.(4-6) Different arrangements of fibers are utilized based on the specific design strength and stiffness or performance requirements that the specific composite is being engineered to meet.(4-6) In particular, glass, carbon, and aramid fibers are commonly used to fabricate FRPs and are referred to as GFRP, CFRP and AFRP, respectively.

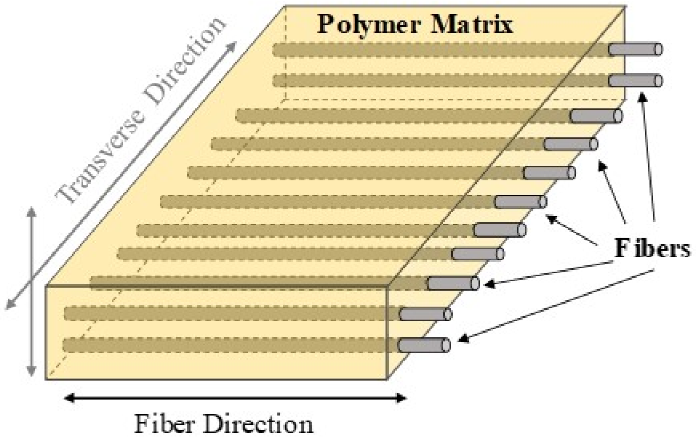

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Figure 1. Schematic representation of a unidirectional FRP composite ply.

It is well known that FRP composites have a high strength-to-weight ratio, excellent corrosion resistance, and the capability to customize the properties of the FRP by altering the material and manufacturing parameters.(4-6) Table 1 shows some key properties (including tensile strength, tensile modulus, density, and specific modulus and strength) of commonly used FRP composites and of conventional structural materials. In general, FRP composites are superior to metals with respect to specific strength and specific moduls. Nevertheless, glass fiber composites have a lower specific modulus than that of both steel and aluminum.

Table 1. Properties of Selected Conventional Structural Materials and FRP Composites.

Material	Material Sub-Type	Fiber Volume Fraction (percent)	Tensile Modulus (ksi)	Tensile Strength (ksi)	Density (lb/in^3)	Specific Modulus (×10^6 in)	Specific Strength (×10^6 in)
Steel	Mild	*	30000	65-120	0.282	106	0.23-0.43
Steel	AISI 1020 HR	*	30000	55	0.283	106	0.19
Steel	AISI 5160 OQT 700	*	30000	263	0.283	106	0.93
Aluminum	2024-T4	*	10600	59	0.098	108	0.60
Aluminum	6061-T6	*	10000	45	0.098	109	0.46
Aluminum	7075-T6	*	10000	83	0.101	99	0.82
FRP Composite	Glass/Epoxy (Unidirectional)	60	4000	114	0.061	66	1.87
FRP Composite	E-glass/Epoxy (Cross-Ply)	57	3118	83	0.071	44	1.17
FRP Composite	Carbon/Epoxy (Unidirectional)	62	19700	278	0.057	345	4.86
FRP Composite	Carbon/Epoxy (Cross-Ply)	58	12040	55	0.056	215	0.98
FRP Composite	Aramid/Epoxy (Unidirectional)	60	11000	200	0.050	220	4.00
FRP Composite	Kevlar 49/Epoxy (Cross-Ply)	60	5800	94	0.051	114	1.84
FRP Composite	Boron/Epoxy (Unidirectional)	60	30000	270	0.075	400	3.60
FRP Composite	Boron/Epoxy (Cross-Ply)	60	15370	55	0.072	213	0.76

*Not Applicable
Source: Adapted from references 4-6.

2.2 Fibers

Fibers are the load-bearing constituents of FRP composites, providing their stiffness and strength.(4-6) In a composite laminate, fibers possess the largest volume fraction. Advanced fibers with high strength and modulus are normally used in FRP composites. Based on molecular structure, they can be categorized as inorganic fibers, carbon fibers, or polymeric fibers.(4-6)

Glass fibers are the most widely used reinforcing fibers in FRP composites. Glass fibers are made from melting raw ingredients (including sand, limestone, alumina, soda ash, etc.) in a refractory furnace and then drawing the molten mixture to form glass fibers from an electrically heated platinum-rhodium alloy bushing (i.e., the direct-melt process).(4-6) In particular, the modifier oxides (including aluminum oxide, calcium oxide, magnesium oxide, boron oxide, etc.) are added to modify glass properties to improve workability. Glass fibers are amorphous solids with tetrahedral structural units of silica (SiO_4), leading fiber properties to be isotropic.(4-6) Individual glass filaments have a diameter ranging from 3 to 25 microns. Immediately after forming the fibers, a water-soluble sizing or a coupling agent is applied to individual filaments to protect them against strength degradation and damage and to enhance the interfacial adhesion of the fibers to the resin matrix. A typical fiberglass strand of 204 parallel filaments is the basic form of commercially used continuous glass fibers and further processed into other textile forms. E-glass and S-glass fibers are commonly used in structural FRP composites.(6)

Basalt fibers are a relatively new reinforcement introduced to structural FRPs and made from basalt stones.(7) Natural basalt is an igneous rock from the solidified volcanic lava. Basalt fibers are produced following a one-stage process (similar to manufacturing process of glass fibers) that involves the melting and homogenization of the basalt followed by the extraction of the fibers.(4-6) Acid basalt with about 46 percent silica (SiO_2) content and low iron content is the only material used for fiber production. The quarried basalt rock is first crushed and washed, then melted at about 1,500 °C, and finally extruded through spinnerets to form continuous fibers. Unlike making glass fiber, no secondary additives are needed during production of basalt fibers. Single basalt filaments are 8 to 20 microns in diameter. Compared with glass fibers, basalt fibers have comparable mechanical properties and excellent high temperature resistance, better than that of glass fibers.(7)

Carbon fibers are the predominant high-modulus and high-strength reinforcing fibers used in high-performance FRP composites. The term “carbon fiber” is used to describe fibers that have a carbon content of 80 to 95 percent, while the term “graphite fiber” describes fibers that have a carbon content above 95 percent.(4-6) Carbon fibers are produced by pyrolysis of a hydrocarbon precursor (i.e., the thermal decomposition of various organic precursor fibers).(4-6) The three most commonly used precursor materials are polyacrylonitrile (PAN), petroleum or coal tar pitch, and rayon. The PAN-based carbon fibers have a relatively low cost, good properties, and are widely used to make structural carbon fibers.(4-6) The precursor-to-carbon fiber conversion process typically takes multiple steps including: (1) spinning the PAN into a precursor fiber; (2) stretching the precursor; (3) stabilization at temperatures lower than 400 °C; (4) carbonization at about 1,500 °C in an inert atmosphere; (5) graphitization at temperatures between 2,000 and 3,000 °C in an inert atmosphere; and (6) surface treatment and application of sizing.(4-6) A single carbon fiber is composed of densely packed hexagonal sheets of covalent-bonded carbon atoms. These sheets are connected to each other with the weak van der Waals bond.(4-6) As a result, carbon fibers are highly anisotropic and their properties strongly depend on the manufacturing process such as the heat-treatment temperature. The diameter of the individual carbon fiber ranges from 4 to 12 microns. A typical carbon fiber tow consists of 400-10,000 filaments, but can be as high as 160,000 filaments.(4)

Aramid fibers are the most important high modulus polymeric fibers and were first developed by DuPont in 1971 with the trade name Kevlar ®.(4-6) The generic name "aramid fiber" is defined as a fiber composed of long chain synthetic polyamide molecules (-CO-NH-) in which at least 85 percent of the amide linkages are connected directly with two benzene rings (i.e., the aromatic polyamides).(4-6) Aramid fibers have the chemical composition of poly paraphenylene-diamine-terephthalamide (PPD-T) that is synthesized by a solution-polycondensation of diamines and diacid halides at low temperatures and the fibers are produced using extrusion and spinning processes.(4-6) The aromatic ring structures in the long chain molecules provide high thermal stability and the para configuration results in high modulus and high strength. Due to the high degree of alignment of long, straight polymer chains along the fiber axis, aramid fibers demonstrate highly anisotropic properties and the tensile strength and modulus are substantially higher in the fiber direction than in the transverse direction.(4-6) The weak hydrogen bonding between the adjacent chains leads to the poor compressive strength of aramid fibers that is about 45 times lower than their tensile strength.(4-6) It is also worth mentioning that the elongation to failure of aramid fibers (approximately 3 percent) is significantly lower than other organic fibers. The diameter of aramid fibers is around 12 microns.(4-6)

Boron fibers were introduced by Talley in 1959 and are considered to be the first commercialized advanced fibers.(6) Boron fibers are manufactured by chemical vapor deposition (CVD) from a process of halide reduction of boron trichloride (BCl_3) with hydrogen on a tungsten or carbon monofilament substrate at temperatures of about 1,300 °C.(5,7) As a result, boron fibers, as produced, are themselves a composite fiber.(5-7) Typically, boron fibers are produced with large diameters on the order of 100, 140, and 200 microns, which contributes to the high resistance of boron fibers to buckling under compressive loads.(4,5) Boron fibers have an amorphous microcrystalline structure and a very high tensile modulus ranging from 55,000 to 60,000 ksi.(5,7)

Representative properties of the aforementioned fibers, as well as their pros and cons, are given in table 2.

Table 2. Properties of Reinforcing Fibers Commonly Used in Structural FRP Composites.

Fiber	Density (lb/in^3)	Tensile Modulus (ksi)	Tensile Strength (ksi)	Pros	Cons
E-Glass	0.0917	10500	500	Low cost, high tensile strength, high chemical resistance, excellent insulating properties	Low tensile modulus, relatively high density, high hardness, relatively low fatigue resistance
S-Glass	0.0900	12400	665	Low cost, high tensile strength, high chemical resistance, excellent insulating properties	Low tensile modulus, relatively high density, high hardness, relatively low fatigue resistance
Basalt	0.0957	12500	580	Low cost, high chemical resistance, high thermal stability, good thermal insulation, environmentally friendly	High brittleness, limited amount of applications, lack of codes and guidelines for use
PAN-Based Carbon	0.0639-0.0708	33360-86300	280-900	High specific modulus and strength, very low coefficient of linear thermal expansion, high fatigue strength	High cost, complex manufacturing process, high brittleness
Pitch-Based Carbon	0.0723-0.0795	24660-142140	330-590	High specific modulus and strength, very low coefficient of linear thermal expansion, high fatigue strength	High cost, complex manufacturing process, high brittleness
Kevlar 29	0.0520	8990	400	High damping coefficient, high impact resistance, low flammability	Hygroscopic, low compressive strength, prone to UV degradation
Kevlar 49	0.0520	18000	525	High damping coefficient, high impact resistance, low flammability	Hygroscopic, low compressive strength, prone to UV degradation
Kevlar 149	0.0520	27000	500	High damping coefficient, high impact resistance, low flammability	Hygroscopic, low compressive strength, prone to UV degradation
Boron	0.0943	58000	500	High modulus, high compressive strength,	Very high cost, high brittleness

Source: Adapted from references 4-7.

2.3 Fiber Architecture

Since fibers provide the stiffness and strength of the FRP composites, properties of FRP composites strongly depend on the arrangement and distribution of fibers, i.e., the fiber architecture. To meet structural design needs, fibers are normally aligned in the loading directions so that the fabricated FRP composites have sufficient strengths to resist the applied loads in these directions.(5,8) Fibrous composites are classified broadly as single-layer and multilayer (angle-ply) composites based on the selected fiber forms.(4-8) Reinforcing fibers in a composite can be short or long compared with their overall dimensions, and are referred to as either discontinuous fiber reinforced composites (short fibers) or continuous fiber reinforced composites (long fibers). Most commonly, fibers in the form of nonwoven, unidirectional, and woven fabrics are used to fabricate structural FRP composites.(5,8)

Nonwoven fabrics (usually seen as "mats" as shown in figure 2) are made from randomly distributed short/chopped fibers that are joined together by mechanical interlocking (i.e., needle punched fabrics) or a chemical binder. By introducing the resin mix into the nonwoven fabric via vacuum infusion, resin transfer molding, and injection or compression molding techniques, random fiber composites can be easily manufactured.(4,5,7) Alternatively, loose short fibers typically in lengths of 1.5 to 2.5 inches (38 to 64 mm) can be sprayed simultaneously with a liquid resin against a mold to form a random FRP composite structure.(4,5,7) Due to the random orientations of fibers, the short fiber composites generally have isotropic mechanical properties. In particular, these composites have better out-of-plane strengths than continuous fiber composites.

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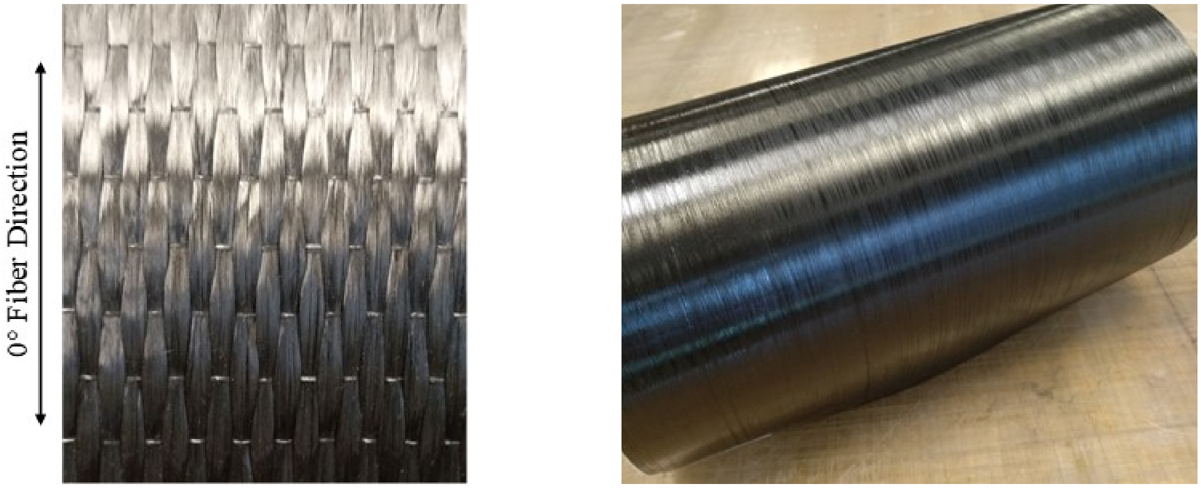
Figure 2. Images showing the nonwoven polyester fiber mat.

Unidirectional (UD) fabrics are composed of long, straight, and continuous fibers of which over 95 percent are distributed parallelly along one direction (i.e., the 0° direction with respect to the longitudinal fiber axis), and the rest of the fibers (the secondary fiber tows) are perpendicular to the primary direction (i.e., the 90° direction) to hold the primary fibers in position.(4-8) Figure 3a shows a typical carbon fiber UD cloth with 12,000-filament tows. UD fabrics represent a basic building block for the formation of laminates or multilayered composites. Since a UD composite has high mechanical properties in the longitudinal direction but weak properties in the transverse direction, multiple UD plies can be stacked in a specific sequence of orientation to fabricate a laminate that can satisfy different design strength and stiffness requirements.(4-8) Nowadays, commercially-available UD prepregs (as shown in figure 3b, a single layer of UD fibers pre-impregnated with a partially cured resin matrix that holds the fibers in position and serves as the matrix after final curing) are often used to fabricate structural FRP composites in forms of the cross-ply ([0/90]) and angle-ply laminates, and quasi-isotropic ([0/+60/-60] and [0/+45/-45/90]) laminates.(4,5,8)



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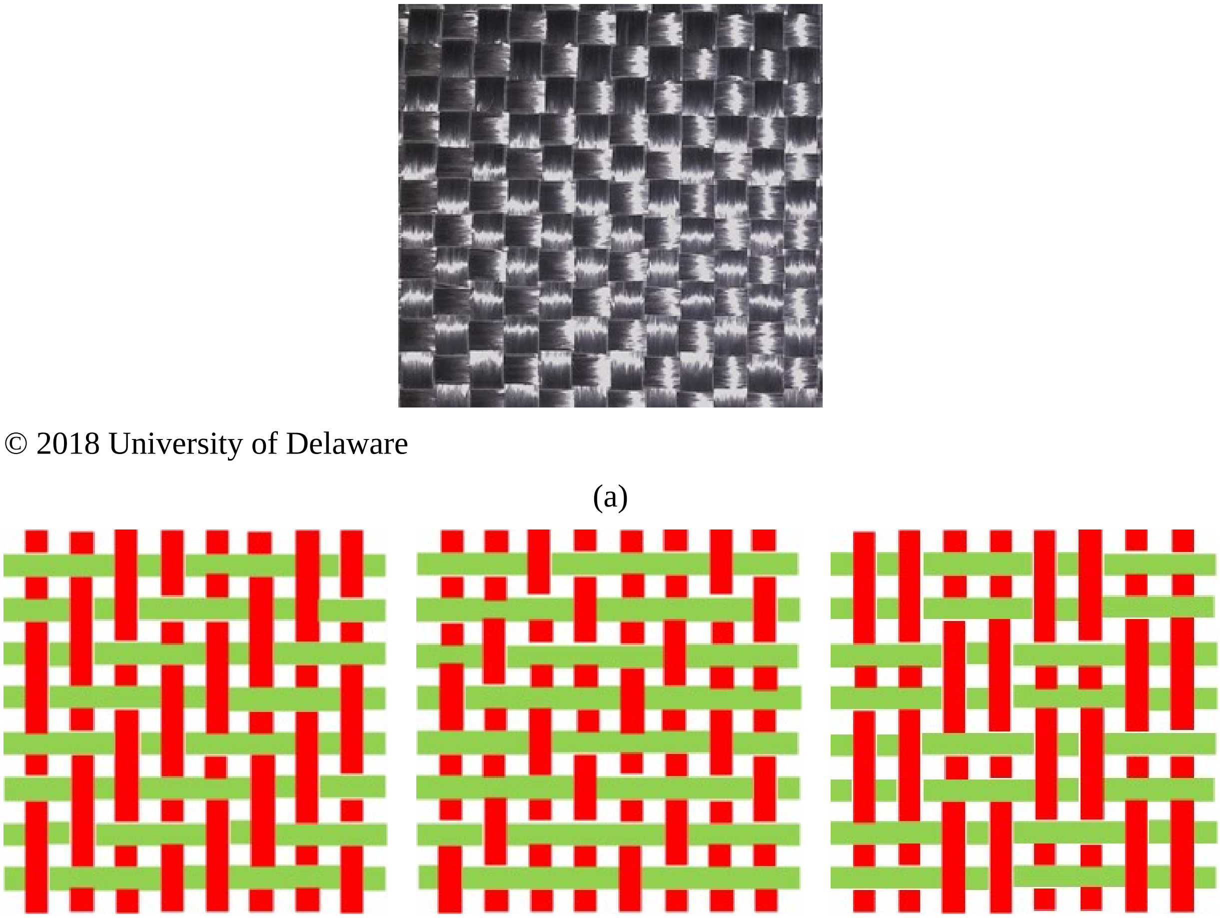
(a)

(b)

Figure 3. Unidirectional fabrics and prepregs (a) carbon fiber unidirectional cloth and (b) unidirectional carbon fiber prepreg.

Woven fabrics are bidirectional fabrics made by interlacing continuous 0° (warp) and 90° (weft) fiber yarns using a weaving loom.(4-6,8) In a woven fabric, warp and weft yarns pass over and under one another following a specific weave style. To produce fabric structures with different weight, drape, and porosity, commonly used weave styles are plain, twill, satin, and basket weave as schematically shown in figures 4a through 4d, respectively. Specifically, in a plain weave, each warp yarn alternately crosses over and under each weft yarn, resulting in a relatively high porosity. Whereas, in the other three weaves, multiple warp yarns alternately pass over and under several weft yarns, creating a dense fabric with high drape. In general, woven fabrics have good integrity and stability due to the mechanical interlocking of the fibers.(5,8) Compared with the stacks of UD plies, the woven fabrics offer better flexibility to conform to the complex surface of nonplanar structures.(5,8) On the other hand, fibers in the woven fabrics are often crimped at the cross-over points, which can decrease the tensile strength of the woven composites and can cause localized resin-rich regions (i.e., pockets of matrix).(4,5,8) In addition, the maximum fiber content of the woven composites is less than it is for UD composites.(4,5,8)



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(a)

(b) (c) (d)

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Figure 4. Woven bidirectional fabrics (a) photograph of a plain weave carbon tow fabric and schematic illustrations showing (b) schematic of a twill 2×2, (c) schematic of a 4-harness satin, and (d) schematic of a 2×2 basket weave.

2.4 Polymeric Matrix

In FRP composites, the structural fibers having specific arrangements are fully embedded in the polymeric matrix and the matrix binds the fibers together, transferring load between them, and protecting them against environmental conditions.(4-6,8) As a result, the matrix directly influences the properties of the bulk FRP composites, such as the transverse modulus and strength, properties in shear and compression, and particularly the service temperature of the composites.(4-6,8)

Polymers (also commonly called plastics) are widely used as the matrix material for fiber composites due to their low cost, ease of use in processing the composite, good chemical resistance, and low weight.(4-6) Polymers are organic, high molecular weight, compounds formed from carbon and hydrogen and represented as long-chain molecules with repeating units (monomers) of molecules that are joined together by strong covalent bonds.(4-6) Polymers are initially in a liquid (monomer) state and later cured at elevated temperatures to attain a solid state that is referred to as matrix. This chemical reaction or curing process is termed polymerization.(4-6) Polymers always show temperature-dependent properties. Increasing temperature causes them to soften, representing a transition from a glassy state to a rubbery state.(4-6) This characteristic temperature is named as the glass transition temperature (T_g). Based on their structure, behavior, and reaction to heating and cooling, polymeric matrixes can be classified into thermoplastics or thermosets.

Thermoplastic polymers are composed of linear or branched-chain molecules that are connected with secondary weak intermolecular bonds, such as van der Waals bonds and hydrogen bonds.(4-6) Upon heating, these polymers can soften and melt into resin at an elevated melting temperature (T_m). When cooled, the molten resin will harden into a new position and become solidified. The melting and solidification of thermoplastics are reversible, enabling the polymers to be reshaped as heated.(4-6) Thermoplastic polymers have either an amorphous or a partly crystalline solid structure. Thermoplastics show degraded mechanical properties when cyclically heated and cooled, but have better impact resistance and toughness than thermosetting polymers.(4-6) Some of the commonly used thermoplastic polymers include polyethylene, polystyrene, polypropylene, nylons, polycarbonate, polyether-ether ketone (PEEK), polyvinyl chloride (PVC), and acrylonitrile butadiene styrene (ABS).

Thermosetting polymers, often referred to as epoxy resins, have linear molecules joined by crosslinks, forming a three-dimensional network structure with covalent bonds between all molecules.(4-6) Thermosetting polymers have been traditionally used as matrix materials for FRP composites. Uncured, raw thermosets are in the form of low molecular weight liquid resins with very low viscosities. Once crosslinks are formed during curing, the resin becomes solidified and cannot be melted and reshaped when re-heated and pressurized. Thermosetting polymers can decompose at high temperatures.(4-6) The curing process of thermosets is an exothermic reaction and usually take place at elevated temperatures or at room temperature in the presence of a catalyst. Compared with thermoplastics, thermosets show much less fluctuations in properties as temperature increases to T_g as a result of their high degree of cross-linking.(4-6) Common examples of thermosetting polymers are epoxies, polyester, vinyl ester, polyurethane, phenolics, and polyimides.

Polyester resin is an unsaturated polyester solid dissolved in a polymerizable monomer such as styrene. Unsaturated polyesters are long-chain linear polymers consisting of a number of reactive C=C double bonds.(4-6) They are cured with conventional organic peroxide or an aliphatic azo compound following an exothermic reaction.(4-6)

Epoxy resins are low-molecular-weight organic liquids having a number of epoxide groups. An epoxide is a three-member ring with one oxygen and two carbon atoms. The most commonly used epoxy resin is diglycidyl ether of bisphenol-A (DGEBA) and higher-molecular-weight species.(4-6) Epoxies are normally mixed with an anhydride or an amine hardener (i.e., curing agent) to become polymerized and form a cross-linked solid network.(4-6) Like polyesters, the curing reaction of epoxies is exothermic and can occur at room temperature. In general, epoxies are superior to polyesters due to their excellent chemical resistance and also their high adhesion to many types of fibers.(4-6)

Vinyl ester resins are unsaturated and closely related to the unsaturated polyesters. They are produced by reacting epoxy resin with acrylic or methacrylic acid and cured with the same conventional organic peroxides that are used with polyester.(5,6) Due to their high molecular weight and the epoxy resin backbone, vinyl esters have good corrosion resistance and mechanical properties combined with toughness and resilience.(5,6)

Polyurethanes consist of organic units joined by carbamate (urethane) links.(5,6) They are normally formed by reacting a di- or tri-poly-isocyanate with a polyol.(5,6) Polyurethanes can be in either a thermosetting or thermoplastic form. Structurally stiff polyurethanes have polymer chains ended in unreacted isocyanate functions which can promote the formation of crosslinks, resulting in relatively higher stiffness.(5,6) They are typically used for structural applications such as bonding structural members and adding stiffness to structural components through a resin injection molding process. On the other hand, the commonly seen flexible urethanes in the form of foams are not considered as a structural material.(5,6)

Properties of commonly used polymeric matrix materials are shown in tables 3 and 4.

Table 3. Properties of Commonly Used Thermoset Polymeric Matrix Materials.

Polymer	Density (lb/in^3)	Tensile Modulus (ksi)	Tensile Strength (ksi)	Glass Transition Temperature T_g (°F)	Pros	Cons
Polyester	0.040-0.051	290-640	5.0-13.0	165-300	Low cost, low viscosity, versatile modifications, fast cure	High volumetric shrinkage, relatively low strength and modulus
Epoxy	0.043-0.047	400-600	8.0-20.0	210-480	Low shrinkage, great chemical resistance and excellent adhesions to fibers	Relatively high cost and viscosity
Vinyl Ester	0.040-0.048	435-510	10.5-12.0	190-390	Low cost and viscosity, fast cure, good moisture resistance and toughness	Slightly more expensive, high volumetric shrinkage

Source: Adapted from references 4-6.

Table 4. Properties of Commonly Used Thermoplastic Polymeric Matrix Materials.

Polymer	Density (lb/in^3)	Tensile Modulus (ksi)	Tensile Strength (ksi)	Glass Transition Temperature T_g (°F)	Melting Temperature T_m (°F)	Pros	Cons
Polyurethane (Rigid)	0.043	260-320	8.7-10.0	-80	460-500	Very good workability, high chemical resistance and impact strength	Very hygroscopic, low heat deflection temperature
PEEK	0.047	470	13.3	290	633	Good mechanical properties, chemical resistance, and toughness	High cost and very high processing temperature
Polycarbonate	0.043	300-350	8.0-9.5	300	310	Good toughness, impact resistance, and workability	Relatively low chemical resistance, moderate toxicity

Source: Adapted from references 4-6.

2.5 Manufacturing Processes

FRP composites with different cross-sectional shapes are produced to resist loads in an efficient manner.(4-6) Structural FRP composites are fabricated in a variety of forms, such as structural shapes, reinforcing bars, and strengthening fabric wraps for retrofitting deficient members (like beams, columns, etc.).(4-6) Generally, the manufacturing of FRP composites involves a series of integrated manual and/or automated processes that enable building up of various layers of fibers and fabrics with resinous materials through wetting and curing them together, or bonding the layers after laminates are assembled.(4-6) The choice of a fabrication method strongly depends on the chemical nature of the matrix material. Specifically, the processing methods for fiber composites using thermosetting matrices generally follow a molding procedure in which fiber/fabric preforms are first formed using specific molds and then resins are introduced and cured during the final formation. These manufacturing processes typically include wet lay-up, spray-up, vacuum-bag molding, resin transfer molding, and pultrusion.(4-6) As for fabricating thermoplastic composites, a shaping method is usually used to first form the composite and then shape the composite into the final part under pressure after melting the thermoplastic matrix.(4-6) Commonly used methods are thermoplastic extrusion, compression molding, and injection molding.

Wet lay-up, also referred to as hand lay-up, is the simplest and most commonly used processing method to make FRP composites. In this method, an open mold made of wood, metal, etc., is first created following the shape and texture of the composite design.(4-6) Next, fiber reinforcements in the form of chopped fibers or continuous woven fabrics are impregnated with resins and placed manually against the mold surface with rollers or brushes.(4-6) Finally, the part is cured in place under standard atmospheric conditions. The hand lay-up process has four common operations including mold preparation, gel coating, hand lay-up, and finishing.(4-6) To have full consolidation and consistent quality of the end product, special care is necessary to ensure complete air removal and resin saturation.

Resin transfer molding (RTM) is a wet impregnation process with a closed-mold. Fibers in the form of mats and UD/woven fabrics are first formed and shaped between the male and female models, and then the resin is introduced under low pressures of roughly 40 to 50 psi (275 to 345 kPa).(4-6) Figure 5 shows a typical RTM setup. A thermosetting resin with relatively low viscosity is used in the RTM process. After the preformed fiber reinforcement is fully saturated with resin (i.e., a full mold), the loaded mold is then heated (or left under the ambient conditions) and cured to produce a composite part. In particular, vacuum can be applied to the outlet of the mold to draw the resin into the mold. With this modification, the male part of the mold (as shown in figure 5) can be replaced with the plastic vacuum bag to reduce the cost of the mold. This modified RTM process is known as vacuum-assisted resin transfer molding (VARTM).(4-6) In general, the RTM process has a high production rate and yields relatively high quality composite parts.(4-6)

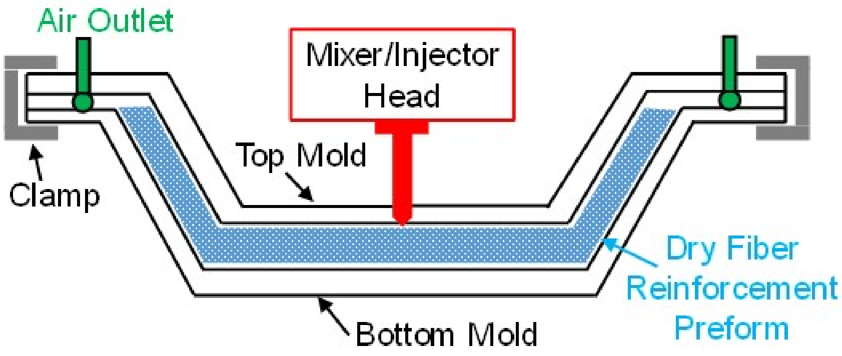

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Figure 5. Schematic illustration showing the resin transfer molding setup.

Pultrusion is an automated process to fabricate solid or hollow continuous FRP structures with constant cross-sections.(4-6) In this process, continuous fiber rovings or fabrics are first impregnated with a resin mix by pulling them through a resin bath. They are then fed through a performer to become partially shaped and to remove any excessive resin and air.(4-6) Due to this process, low viscosity thermosetting resins are used. Next, the saturated fiber sections are passed into a heated die and are in turn continuously cured. After curing, the hardened FRP product is cut to the desired length.(4-6) Figure 6 depicts the pultrusion process. In general, the pultrusion process is a fast and economic method for fabricating continuous FRP shapes with relatively high fiber volume fractions.(4-6)

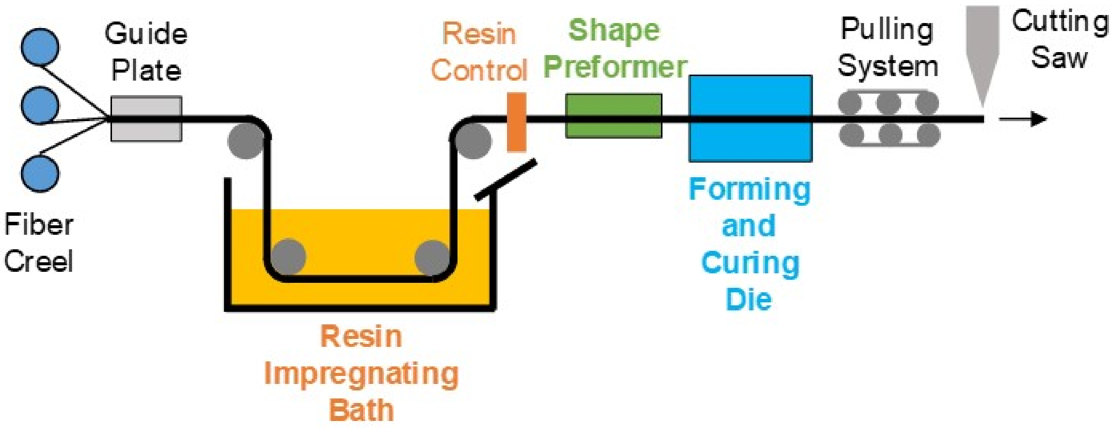

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Figure 6. Schematic illustration showing a pultrusion process.

Thermoplastic extrusion is similar to the pultrusion process and used to make continuous FRP structures with thermoplastic matrix materials.(5,6) In this process, the thermoplastic polymer is heated and melted through a long horizontal chamber within the extrusion machine, and then forced into a hot die (or mold) in which the fiber/fabric preforms are loaded (i.e., an injection molding operation).(5,6) Next, the entire molten material is consolidated under pressure in the die/mold and continuously pushed out. Finally, the extruded material is cooled through water immersion or an air-blowing technique to form the final FRP product.(5,6) Figure 7 schematically presents an extrusion process. In particular, the extrusion process is beneficial for reforming and repairing thermoplastic FRP structures. Compared with thermoset pultrusion, this process requires high heat and pressure, causing high operation costs. In addition, the extruded FRP parts are normally low in fiber volume fractions (less than 30 percent) due to the high viscosity of the thermoplastic matrix.(5,6)

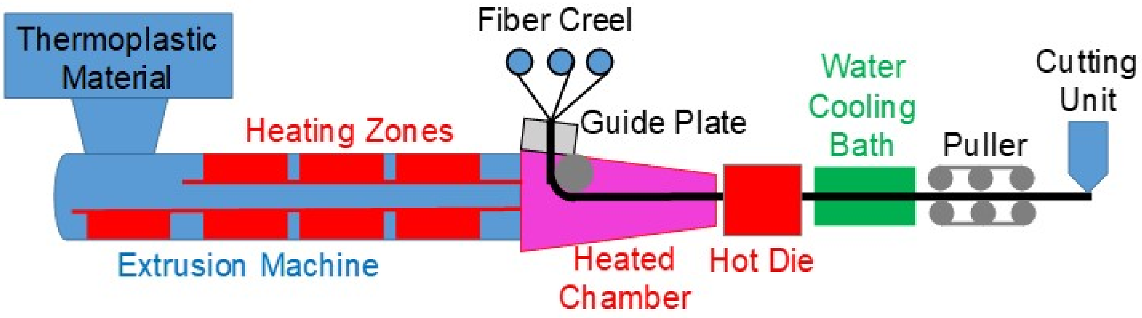

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Figure 7. Schematic illustration showing a thermoplastic extrusion process.

Compression molding, similar to injection molding, is a common molding process used to fabricate FRP parts with both thermoset and thermoplastic matrixes.(4-6) In this process, the raw feeding materials (also called “charge”) consist of mainly the preformed molding compounds (i.e., a mixture of a resin, fiber reinforcement, and additives), such as the bulk molding compounds (BMC), sheet molding compounds (SMC), prepregs, and glass mat thermoplastics (GMT).(4-6) These compounds, or raw materials, are directly placed in the mold cavity and compressed under pressure and heat. In this way, the thermoset matrix material cures under the applied heat and the thermoplastic matrix material becomes melted and forms to the shape of the mold.(4-6) Figure 8 illustrates compression molding equipment. It is worth mentioning that compression molding is the fastest method for making structural FRP parts.

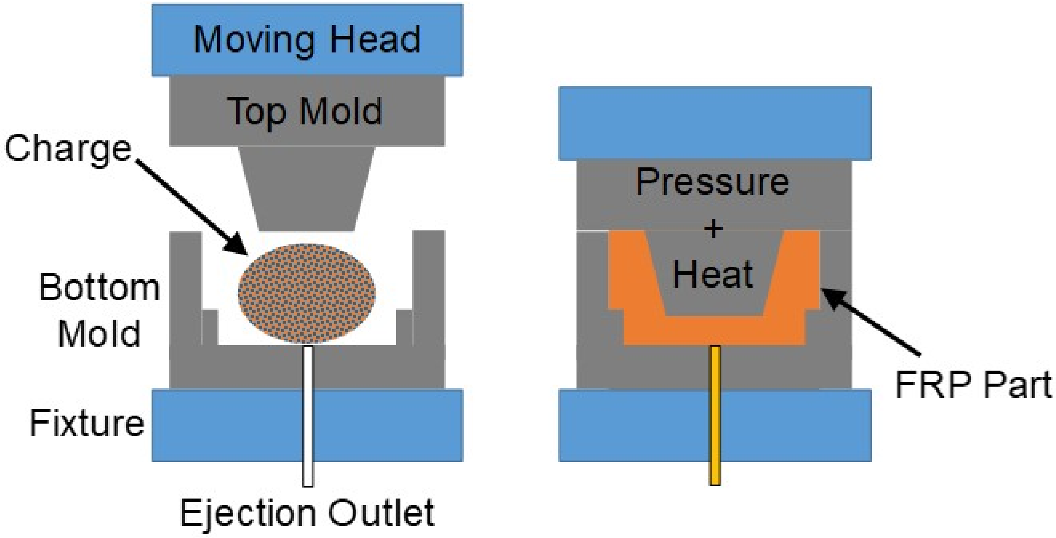

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Figure 8. Schematic illustration showing a compression process.

CHAPTER 3. TRADITIONAL AND EMERGING METHODS FOR BRIDGE STRENGTHENING

This chapter will first discuss evaluating the need for structural strengthening, followed by traditional and emerging methods for strengthening bridges.

3.1 Confirming the Need for Bridge Strengthening

The cost of retrofitting a bridge and the associated user costs related to disruption of traffic are often quite substantial. While this report focuses on identifying appropriate methods for increasing a bridge's capacity through retrofit and strengthening, it is important to note that the first step in the process is to determine whether or not the candidate bridge actually needs to be strengthened.

While visual inspection and standard analysis may indicate strengthening is needed, more advanced and increasingly economic evaluation techniques are now available that can provide better information from which the need for strengthening can be more reliably determined. These methods include (1) refined analysis (see the Task 2 Report on LRFD Specification and Refined Analysis of this FHWA-HIF-18 report series) and (2) bridge evaluation using field test results. It has been shown that utilizing the results of these techniques can provide a more accurate condition assessment of the bridge in question. Since these techniques can often be conducted at a fraction of the cost of a complete retrofit, and since they can, in some cases, be used to show that existing bridges are, in fact, not in need of strengthening, it is recommended that engineers consider the benefit of implementing either advance analysis or field testing prior to designing and implementing an extensive retrofit.

3.2 Prior Reports on Bridge Strengthening

In 1987, NCHRP Report 293, Methods of Strengthening Existing Bridges was published.(2) It documented a comprehensive effort to evaluate the feasibility and cost effectiveness of bridge strengthening methods in existence at that time. The tasks of the project included (1) thoroughly reviewing and contacting appropriate organizations to identify and describe bridge strengthening techniques, (2) determining which structures show the greatest need for broad applications of strengthening, (3) evaluating the cost effectiveness of traditional methods and innovative techniques, (4) preparing a manual for use by practicing engineers that describes the most effective techniques for strengthening, and (5) preparing a final report.

Ten years later, in 1997, NCHRP Synthesis 249, Methods for Increasing Live Load Capacity of Existing Highway Bridges, updated the findings of the 1987 report.(1) The Synthesis 249 project relied on Report 293 for the detailed descriptions of strengthening methods reported on in 1987, but provided an update of each method. The Synthesis 249 report also identified several emerging methods.

3.3 Traditional Methods of Bridge Strengthening

As documented in NCHRP Report 293, and further presented in NCHRP Synthesis 249, traditional strengthening techniques that utilize common construction materials include (1) reduced dead load, (2) lightweight decks, (3) development of composite action, (4) improved member strength, (5) increased transverse stiffness, (6) adding or replacing members, (7) strengthening connections, (8) post-tensioning members, and (9) development of bridge continuity.(1,2) These two reports provide a comprehensive overview of the mentioned traditional strengthening techniques, as well as details for each.

3.4 New and Emerging Methods of Bridge Strengthening

In 1997, NCHRP Report 293 identifying several new emerging methods including (1) aluminum decks, (2) fiber-reinforced concrete decks, (3) fiber-reinforced composite decks, (4) member strengthening using of post-tensioning, (5) fiber reinforce polymers (FRP), (6) partial end restraint, and (5) bonded FRP laminates.(2) The report also concluded that epoxy bonded steel plates, a technique identified as emerging in 1987, was unlikely to be widely applied.

A primary focus of the current project was to identifying newly emerging methods being used for bridge repair and strengthening that have appeared over the twenty years since NCHRP Report 293 was published.(2) This includes updates on the emerging methods discussed in the 1997 report, as well as the identification of new methods.

New methods were identified through an extensive literature review, information collected by FHWA as a part of the Innovative Bridge Research & Construction (IBRC) and Innovative Bridge Research & Deployment (IBRD) projects, and surveys distributed to members of select AASHTO, FHWA, and TRB groups and committees.(3)

In terms of the literature review, databases including Web of Science, Compendex (Engineering Village), ASCE, and TRID were used. This literature search was not meant to yield a comprehensive list of all research and bridge strengthening projects that have been completed since 1997, but rather provide a representative sample of the new types of strengthening methods being researched and implemented in the field. Nearly 90 percent of the reports and papers found involved applications of advanced composite materials (ACM).

The Innovative Bridge Research and Construction (IBRC) and Innovative Bridge Research and Deployment (IBRD) Programs were created by FHWA in an effort to encourage State DOTs to implement new technologies in bridge repair and new bridge construction. Reports were collected from the States that detailed lessons learned from their experiences and the results were compiled into an unpublished report.(9) IBRC reports were reviewed as part of the literature search for this project. About 85 percent of the IBRC/IBRD repair or strengthening projects involved use of fiber reinforced polymer (FRP) composites as the innovative technology.

The following sections provide descriptions, as well as advantages and disadvantages, of new bridge strengthening methods which have been developed since the 1997 synthesis report. These methods include (1) externally bonding FRP, (2) near-surface-mounting composites, (3) post-tensioning of FRPs, (4) fiber reinforced cementitious matrix as a strengthening system, (5) spray FRP as a strengthening system, (6) column retrofitting with composites, and (7) experimental research on emerging applications. Within these seven area, based on associated projects completed-to-date by state DOT's, the most prevalent applications of composite materials for use in bridge strengthening and rehabilitation have been externally bonded FRP, near-surface-mounted composites, and column retrofitting with composites.

3.4.1 Externally Bonded FRP

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy. A sample application is shown in figure 9. In the literature this method is also called epoxy bonding.(10-26) This report will use the term externally bonded (EB) FRP. FRPs can be bonded in the form of strips, plates, sheets, or wraps. For pre-cured composite plates, a layer of epoxy acts as an adhesive between the plate and the structure, while dry fiber sheets are applied on site where the epoxy then forms the polymer matrix of the composite and also acts as the adhesive when it cures. The curing time required for the epoxy to form the bond between the structure and the FRP composite is a matter of hours, so traffic closures are minimal. Some research has been conducted to suggest that the strength of the FRP bond is not affected by traffic loading, so traffic it may be possible for the bridge to remain open during repair.(10)

(Courtesy of Minnesota DOT)

Figure 9. Photograph showing an externally bonded FRP repair.

Fiber sheets are most commonly applied by hand where the epoxy is spread with a trowel. Research is ongoing to try to implement vacuum assisted resin transfer molding (VARTM) in the field. This application method involves sealing the FRP material to the structure with an air tight covering and creating a vacuum through which the epoxy is pulled from one end of the repair to the other by a machine. VARTM yields a better, stronger bond due to even and thorough distribution of epoxy.

EB FRPs provide an alternate load path for the structure, which increases the structural capacity. EB FRPs also prevent existing cracks from opening and propagating and prevent future cracks from forming, which restores capacity lost due to cracking and prolongs the structure's service life. By controlling the opening of cracks, the bonded FRP often improves the stiffness of the member as well. EB FRPs also protect the structure from concrete deterioration and steel corrosion.

FRPs can be bonded to the tension face of concrete, steel, or timber beams to increase flexural capacity, or to the sides of beams to increase shear capacity. FRP fabric wraps have also been used for axial, flexure, and shear strengthening of columns, and to provide added impact resistance. Research is ongoing to extend the application of EB FRP to fatigue repair and torsional strengthening.

One drawback of EB FRP is that the ends of the FRP are vulnerable to peeling or delaminating from the structure due to high shear stresses at the end locations, which results in a loss of strength. Research has been conducted to prevent delamination including beveling the edges of pre-cured plates and anchoring the ends of the repair material. Anchors can include additional strips of composite material applied transversely across the end of the repair or mechanical fasteners.

In an effort to prevent delamination and "peeling" of FRP repairs, mechanical fasteners are being used to install FRPs in an increasing number of applications. This method is referred to as mechanically fastened (MF) FRP. These fasteners include concrete screws, steel powder-actuated fastened (PAF) pins, and steel anchors. Research has shown that a combined system of externally bonded and mechanically fastened FRP material provides the most reliable strengthening effect. The use of mechanical fasteners also allows for easier post-tensioning of the FRP material, which can increase the amount of strength gained from the retrofit.

3.4.2 Near Surface Mounted Composites

Another method utilized to minimize debonding is near surface mounting.(27-44) This method involves cutting a groove in the surface of the member, applying epoxy, placing the FRP material, and filling the remaining space with epoxy. A sample application is shown in figure 10. "The principle of NSM reinforcement is to introduce additional reinforcement into the concrete section in such a way that it acts compositely with the rest of the section in the same way as if it were cast into the concrete."(27) The grooves can be cut longitudinally, vertically, or diagonally on the member and can vary in length depending on the application. FRP strips, plates, and both circular and rectangular rods have been near surface mounted. With this method, three sides of the FRP are bonded to the concrete member, which minimizes the chance for debonding and increases force transfer. This method also offers greater protection to the retrofit from environmental impacts. Near surface mounting provides a significant increase in moment capacity with relatively little repair material. NSM FRP bars can be prestressed in order to utilize more strength of the composite.

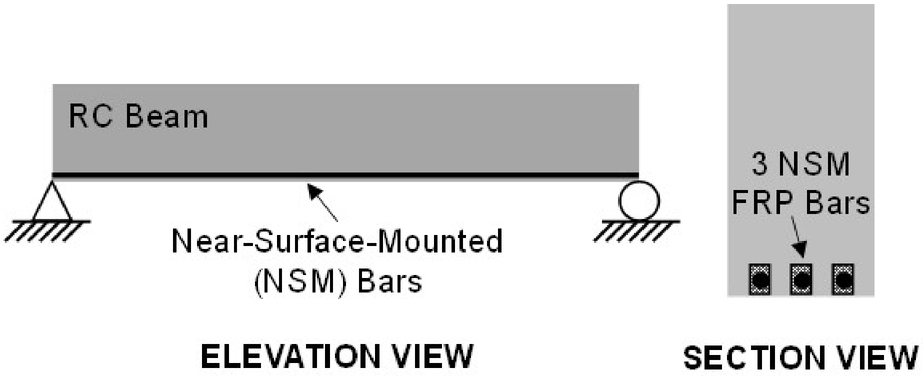

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Figure 10. Schematic showing near surface mounted composites.

3.4.3 Post-Tensioning of FRPs

Post-tensioning is not a new method, but it can be applied to many of the new methods that utilize composites.(45-50) Post-tensioning introduces a tensile force in a material, such as an FRP strip or rod, which is to be installed or attached to a base structure, usually a beam (see sample application in figure 11). The force is released after the material is installed, thereby creating a compressive force in the base structure and possibly a moment if the material was applied eccentrically to the structure. The induced forces and moments are designed to counteract the forces and moments caused by the loading on the structure, thereby increasing the structure's overall capacity.

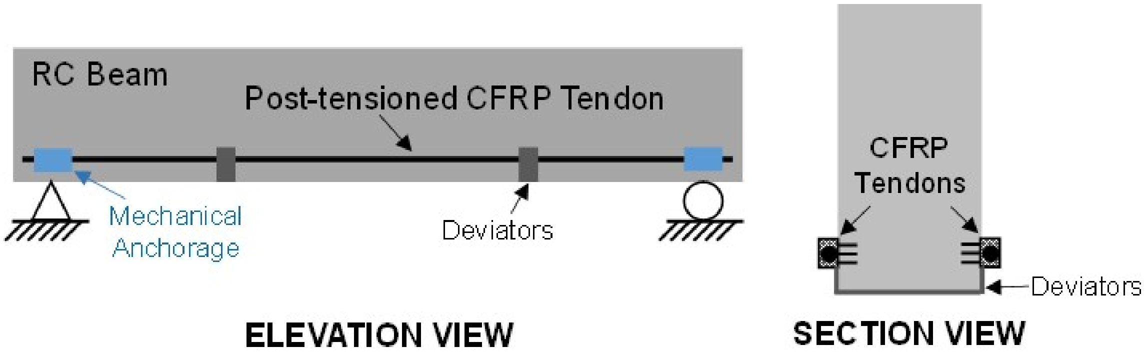

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Figure 11. Schematic showing post-tensioning of FRPs.

3.4.4 Fiber Reinforced Cementitious Matrix as a Strengthening System

Fiber Reinforced Cementitious Matrix (FRCM) "is a composite material consisting of one or more layers of cement-based matrix reinforced with dry-fiber fabric."(51) The dry fiber sheets are placed against the structure being strengthened and a cement-based mortar is applied with a trowel to form the matrix of the composite and to bond the system to the structure.(51-62) A sample application is shown in figure 12. Fiber reinforced cementitious matrix provides many benefits over FRP laminates, including a water-based inorganic binder, resistance to UV radiation, permeability compatibility with concrete, and conistent workability between 40 and 105 degrees F (4.4 and 40.6 degrees C).(52) The cement-based mortar is more compatible with concrete structures than epoxy and produces a stronger bond. Carbon and glass fiber sheets are mostly used as reinforcement for FRCM, but steel fiber sheets are also being researched.

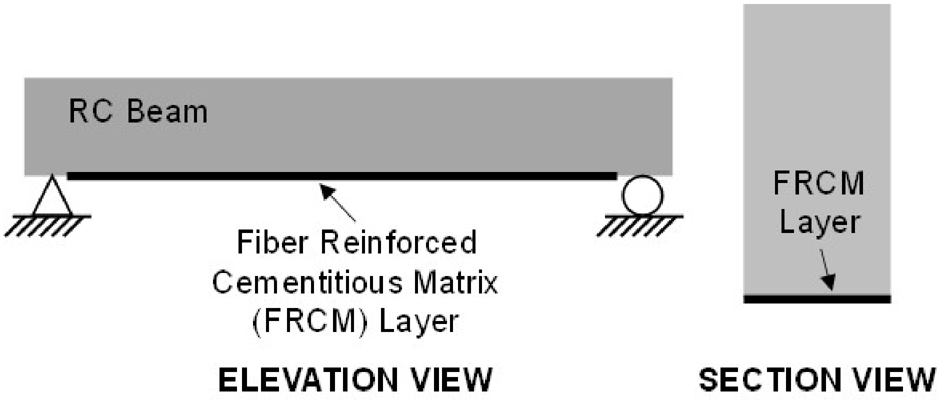

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Figure 12. Schematic showing fiber reinforced cementitious matrix as a strengthening system.

3.4.5 Spray FRP as a Strengthening System

Spray FRP was pioneered at the University of British Columbia and involves using a spray gun to spray polymer and short, randomly distributed fibers concurrently on the surface of the concrete to be repaired resulting in a 2-dimensional random distribution of fibers applied to the structure surface.(63) A sample application is shown in figure 13. The applicability of rehabilitating concrete beams with spray FRP is an area of ongoing research.(64-69) Laboratory results indicate that spray FRP performed at least as well if not better than the continuous FRP wraps.(64) The SFRP method was applied in the field on Safe Bridge on Vancouver Island to repair severe spalling.(65) A field test conducted three years after the repair showed that the spray FRP was in similar condition as when just applied and future delamination was unlikely.

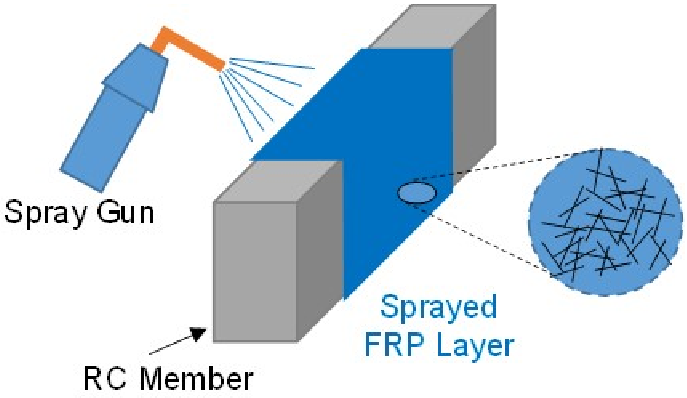

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Figure 13. Schematic showing spray FRP as a strengthening system.

3.4.6 Column Retrofitting with Composites

The use of FRP column wraps for seismic performance (largely to improve ductility of reinforced concrete columns) was not within the scope of this project. That application is quite mature and has been used extensively in seismic regions along with steel jackets. A sample application is shown in figure 14.

However, several studies have shown that FRP confinement of concrete columns can also be used in non-seismic applications to restore, improve, and in some cases surpass the original design strength of the member.(70) There is a need for fast, durable, and cost-efficient repair methods for columns damaged due to impact or deterioration, and wrapping columns with FRP is a viable solution.(70) Numerous column field retrofits are covered in the literature.(3,9,71-80)

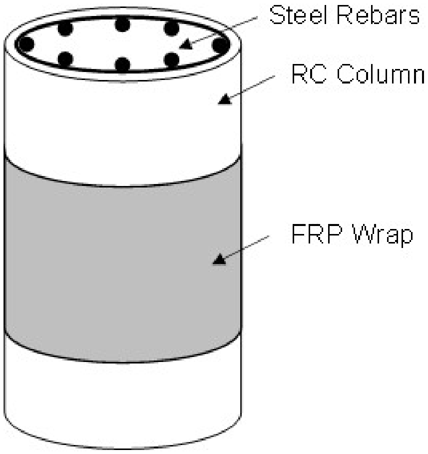

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Figure 14. Schematic showing column retrofitting with composites.

3.4.7 *Modifying the Bridge Structure*

Another approach to strengthen a bridge is to modify the overall structure to increase its strength. Converting simple span bridges to continuous span bridges, or converting non-integral abutments to integral abutments are two such options.(81-87) A sample application is shown in figure 15.

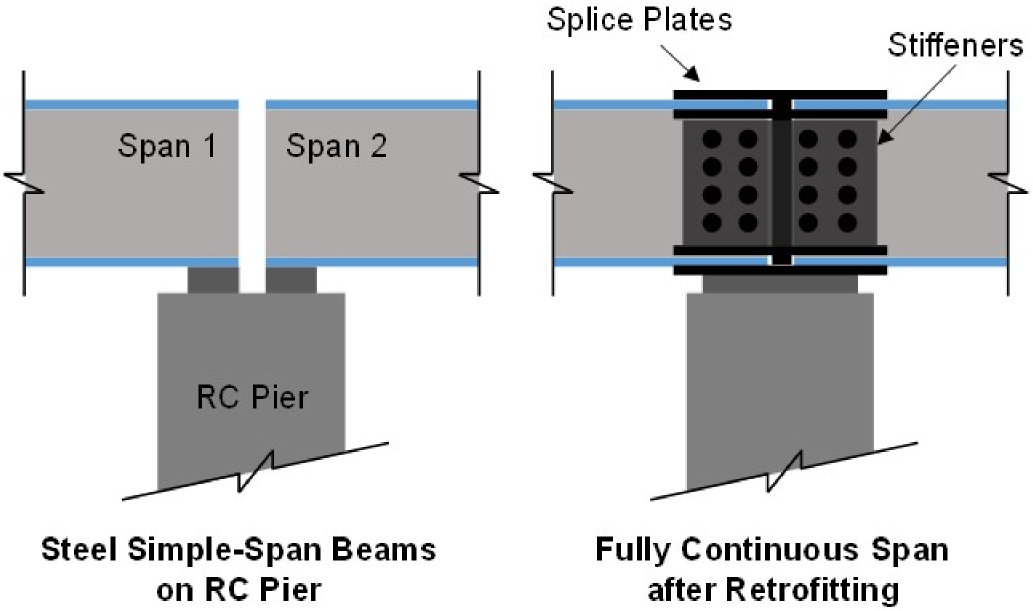

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Figure 15. Schematic showing modification of a bridge structure.

3.4.8 *Experimental Research on Emerging Applications*

Other emerging and largely experimental approaches for using composites include (1) repair of impact damaged girders, (2) repair of fatigue damaged steel structures, (3) strengthening of arches, (4) torsional member strengthening, (5) use of FRP beams, (6) improved resistance to buckling, and (6) concrete-filled tube arches.(3,9,88-112) In addition, research is ongoing to better understand and to improve the properties and performance of composites for bridge applications. These efforts are being conducted in the following areas, (1) making composites or systems with composites behave/fail in a more ductile manner, (2) use of vacuum-assisted resin transfer molding (VARTM) to improve bonding, (3) understanding fatigue behavior, and (4) understanding the effects of traffic loads on FRP.(113-130)

CHAPTER 4. NATIONAL SPECIFICATIONS FOR TRADITIONAL AND COMPOSITE MATERIAL APPLICATIONS

This chapter presents the most commonly used specifications and guidelines for designing bridge strengthening retrofits using both traditional and composite materials.

4.1 Overview

Specifications provide design guidelines and procedures that ensure that all critical design requirements are met. Over the years, the American Association of State Highway and Transportation Officials (AASHTO) has developed and maintained specifications for bridge design and evaluation.(131-133) These specifications primarily focus on bridges that are built and repaired using traditional materials. Additional guidelines and manuals for design using traditional materials are provided by the American Concrete Institute (ACI) and the American Institute for Steel Construction (AISC).(134-136)

In recent years, numerous guidelines have been developed for the design of composite material applications since these materials are not covered in the more traditional AASHTO codes. These guidelines, developed by AASHTO, ACI, and the National Cooperative Highway Research Program (NCHRP), were based on the extensive research that has been conducted around the world, and cover a variety of applications.

4.2 National Guidelines and Specifications

Below are AASHTO, ACI, and AISC specifications and manuals that can be used for developing strengthening designs when using traditional materials.

- AASHTO. 2014. *LRFD Bridge Design Specification, Customary U.S. units*. 7th ed. Washington, DC: American Association of State Highway and Transportation Officials.
- AASHTO. 2011. *Manual for Bridge Evaluation*. 2nd ed., with 2016 interim revisions. Washington, DC: American Association of State Highway and Transportation Officials.
- AASHTO. 2003. *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges*. 1st ed., with 2005 interim revisions. Washington, DC: American Association of State Highway and Transportation Officials.
- ACI. 2014. *Building Code Requirements for Structural Concrete and Commentary*. ACI 318-14. Farmington Hills, MI: American Concrete Institute.
- AISC. 1997. *Torsional Analysis of Structural Steel Members*, Steel Design Guide Series. Chicago, IL: American Institute for Steel Construction.

- AISC. 1989. *Manual of Steel Construction – Allowable Stress Design*, 9th ed. Chicago, IL: American Institute for Steel Construction.

Below are the AASHTO, ACI, and NCHRP guidelines and specifications that have been developed for use in strengthening structures with composite materials.(137-151) These documents should be consulted when retrofitting bridges with composite materials and used in conjunction with the AASHTO LRFD Bridge Design Specifications, the AASHTO Manual for Bridge Evaluation, the ACI Building Code Requirements, and the AISC Manual of Steel Construction.(131,132,134,136)

- AASHTO. 2019. *LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings*, 1st ed. Washington, DC: American Association of State Highway and Transportation Officials.

- AASHTO. 2012. *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*, 1st Edition. Washington, DC: American Association of State Highway and Transportation Officials.

- AASHTO. 2012. *LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes for Flexural and Axial Members*, Washington, DC: American Association of State Highway and Transportation Officials.

- ACI. 2014. *Specification for Carbon and Glass Fiber-Reinforced Polymer FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures*. ACI 440.8-13. Farmington Hills, MI: American Concrete Institute.

- ACI. 2012. *Guide Test Methods for Fiber-Reinforced Polymers FRPs) for Reinforcing of Strengthening Concrete Structures*. ACI 440.3R-12. Farmington Hills, MI: American Concrete Institute.

- ACI. 2010. *Guide for Design and Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures*. ACI 440.7R-10. Farmington Hills, MI: American Concrete Institute.

- ACI. 2008. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. ACI 440.2R-08. Farmington Hills, MI: American Concrete Institute.

- ACI. 2013. *Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures*. ACI 549.4R-13. Farmington Hills, MI: American Concrete Institute.

- NCHRP. 2003. *Application of Fiber Reinforced Composites to the Highway Infrastructure*. NCHRP Report 503. Washington, DC: Transportation Research Board.

- NCHRP. 2004. *Bonded Repair and Retrofit of Concrete Structures Using FRP Composites: Recommended Constructions and Process Control Manual*. NCHRP Report 514. Washington, DC: Transportation Research Board.

- NCHRP. 2006. *Field Inspection of In-Service FRP Bridge Decks*. NCHRP Report 564. Washington, DC: Transportation Research Board.

- NCHRP. 2008. *Design Guidelines for Durability of Bonded CFRP Repair/Strengthening of Concrete Beams*. NCHRP Report 155. Washington, DC: Transportation Research Board.

- NCHRP. 2008. *Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites*. NCHRP Report 609. Washington, DC: Transportation Research Board.

- NCHRP. 2010. *Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*. NCHRP Report 655. Washington, DC: Transportation Research Board.

- NCHRP. 2011. *Design of FRP Systems for Strengthening Concrete Girders in Shear*. NCHRP Report 678. Washington, DC: Transportation Research Board.

CHAPTER 5. STATE DOT DESIGN CRITERIA AND SPECIFICATIONS FOR COMPOSITE MATERIALS APPLICATIONS

During the past two decades, hundreds of bridges worldwide have been strengthened using fiber reinforced composites. Since FRP composites are a relatively new construction material, and design criteria and specifications for these advanced materials are evolving, these field projects have largely been treated as “demonstration” projects by state DOTs and many involved close collaborations with research organizations. Different types of FRP materials (such as GFRP and CFRP) and FRP elements (reinforcing bars, strengthening patches/wraps, and hybrid structural components) have been utilized in these demonstration projects. Significant amounts of useful information with respects to design, construction, and performance has been collected by a variety of states. The findings have enabled various states to publish their own design criteria and specifications, as well as document their experiences and lessons learned. In the following sections, FRP applications and design specifications from some of the states most active in the implementation of composite materials for bridges are reviewed.

5.1 Florida DOT (FDOT)

The Florida Department of Transportation (FDOT) has published updated and comprehensive guidelines for using FRP composites as structural materials. Basic design guidelines for FRP reinforcing bars, externally-bonded systems, and structural shapes are included in their structures manual.(152)

- 2018. *Structures Manual, Volume 4: Fiber Reinforced Polymer Guidelines FRPG*. Tallahassee, FL: Florida Department of Transportation.

FDOT has also suggested recommendations regarding the durability of FRP composites in the following reports.(153,154)

- 2017. *Durability Evaluation of Florida’s Fiber-Reinforced Polymer FRP) Composite Reinforcement for Concrete Structures*. Report BDV31-977-01. Tallahassee, FL: Florida Department of Transportation.
- 2014. *Highly Accelerated Lifetime for Externally Applied Bond Critical Fiber-reinforced Polymer FRP) Infrastructure Materials*. Report BDK75-977-45. Tallahassee, FL: Florida Department of Transportation.

5.2 California DOT (Caltrans)

The California Department of Transportation (Caltrans) has developed Load and Resistance Factor Design (LRFD) guidelines for FRP strengthening systems for reinforced concrete structures.(155)

- 2006. *Development of Load and Resistance Factor Design for FRP Strengthening of Reinforced Concrete Structures*. Report UCSD/SSRP-06/13. Sacramento, CA: California Department of Transportation.

5.3 Maine DOT

The Maine DOT has recently performed a series of projects using FRP composites as both strengthening systems and structural components of bridges. Specific design and construction guidelines have been proposed for FRP piles, structural FRP tubes, and FRP-based strengthening materials. These recommendations are included in several documents.

Structural FRP tubes(156-158)

- 2015. *Bridge-in-a-BackpackTM-Task 3.3: Investigating Soil-Structure Interaction-Modeling and Experimental Results of the concrete filled FRP tubes arches*. Report ME 16-04. Augusta, ME: Maine Department of Transportation.
- 2016. *Bridge-in-a-BackpackTM-Task 6: Guidelines for Long Term Inspection and Maintenance.* Report ME 16-12. Augusta, ME: Maine Department of Transportation.
- 2016. *Bridge-in-a-BackpackTM-Task 5: Guidelines for Quality Assurance*. Report ME 16-13. Augusta, ME: Maine Department of Transportation.

FRP-based piles(159,160)

- 2015. *Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles-Task 4A-Design Specifications*. Report ME 17-1. Augusta, ME: Maine Department of Transportation.
- 2015. *Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles-Task 4B-Material and Construction Specifications*. Report ME 17-2. Augusta, ME: Maine Department of Transportation.

FRP strengthening systems(161,162)

- 2014. *Advanced Bridge Safety Initiative: FRP Flexural Retrofit for Concrete Slab Bridges-Task 4 Deliverables*. Report ME14-08. Augusta, ME.
- 2014. *Culvert Rehabilitation Guidance*. Augusta, ME: Maine Department of Transportation.

5.4 Texas DOT

The Texas DOT has conducted several projects involving the long-term performance and durability of the FRP strengthening systems, especially under harsh environments. Furthermore, they have also developed specific design guidelines for FRP structural systems.(163-166)

- 2001. *Effects of Wrapping Chloride Contaminated Concrete with Fiber Reinforced Plastics*. Report FHWA/TX-03/1774-2. Austin, TX: Texas Department of Transportation.
- 2002. *Composite Structural Members for Short Span Highway Bridges*. Report 1173-1. Austin, TX: Texas Department of Transportation.
- 2004. *Detailed Evaluation of Performance FRP Wrapped Columns and Beams in a Corrosive Environment*. Report FHWA/TX-05/0-1774-3. Austin, TX: Texas Department of Transportation.

- 2006. *Performance of Fiber Composite Wrapped Columns and Beams in a Corrosive Environment*. Report FHWA/TX-07/0-1774-4. Austin, TX: Texas Department of Transportation.

The Texas DOT has also performed several projects involving the application of FRP structural systems in terms of FRP bars, FRP wraps, and FRR anchors. Associated design and construction recommendations for these applications have been developed.(167-171)

- 2004. *Characterization of Design Parameters for Fiber Reinforced Polymer Composite Reinforced Concrete Systems*. Report FHWA/TX-05/9-1520-3. Austin, TX: Texas Department of Transportation.
- 2005. *Preliminary Quality Control/Quality Assurance Standards Criteria) for Inspection and Testing of FRP Bars*. Report FHWA/TX-05/9-1520-P1. Austin, TX: Texas Department of Transportation.
- 2005. *Design, Construction, and Maintenance of Bridge Decks Utilizing GFRP Reinforcement*. Report FHWA/TX-05/9-1520-P2. Austin, TX: Texas Department of Transportation.
- 2015. *Use of Carbon Fiber Reinforced Polymer CFRP) with CFRP Anchors for Shear-Strengthening and Design Recommendations/Quality Control Procedures for CFRP Anchors*. Report FHWA/TX-16/0-6783-1. Austin, TX: Texas Department of Transportation.
- 2017. *Repair Systems for Deteriorated Bridge Piles: Final Report*. Report FHWA/TX-17/0-6731-1. Austin, TX: Texas Department of Transportation.

5.5 Kentucky Transportation Cabinet (KYTC)

The Kentucky Transportation Cabinet (KYTC) has been conducted FRP-related projects since 1996 and has applied FRP composites as both strengthening systems and new structural components. In particular, KYTC has implemented over 20 projects involving externally-bonded FRP composites for strengthening and retrofitting of in-service bridges. Design and construction guidelines have been recommended by KYTC for FRP wraps as well as FRP-rebar reinforced bridge decks.(172-176)

FRP wraps(172-176)

- 2002. *Shear Strength of R/C Beams Wrapped with CFRP Fabric*. Report KYTC-02-14/SPR 200-99-2F. Frankfort, KY: Kentucky Transportation Cabinet.
- 2006. *Shear Repair of P/C Box Beams Using Carbon Fiber Reinforced Polymers CFRP) Fabric*. Report KYTC-06-01/FRT114-01-1F. Frankfort, KY: Kentucky Transportation Cabinet.
- 2007. *Retrofit of the Louisa-Fort Gay Bridge Using CFRP Laminates*. Report KYTC-07-08/FRT118-03-1F. Frankfort, KY: Kentucky Transportation Cabinet.
- 2013. *Repair of I-65 Expressway Bridges Using Carbon Fiber Reinforced Polymer CFRP) Composites*. Report KYTC-13-16/FRT126-03-1F. Frankfort, KY: Kentucky Transportation Cabinet.

- 2017. *CFRP Strengthening of KY 583 Over the Bluegrass Parkway Bridge in Hardin Country*. Report KYTC-17-19/KHIT88-06-1F. Frankfort, KY: Kentucky Transportation Cabinet.

FRP rebar:(177,178)

- 2000. *GFRP Reinforced Concrete Bridges*. Report KYTC-00-9. Frankfort, KY: Kentucky Transportation Cabinet.
- 2006. *Field Inspection and Evaluation of a Bridge Deck Reinforced with Carbon Fiber Reinforced Polymer (CFRP) Bars*. Report KYTC-06-06/FRT102-00-1F. Frankfort, KY: Kentucky Transportation Cabinet.

5.6 Virginia DOT (VDOT)

The Virginia Department of Transportation (VDOT) has investigated the design and performance of bridge components made of FRP composites, such as FRP girders and FRP decks under service conditions. VDOT has also investigated the design and performance of GFRP bars used in bridge structures. In particular, VDOT recently conducted studies on full-scale hybrid composite beams that consists of a concrete tied arch encased in an FRP composite shell. Design and construction specifications recommended by VDOT can be found in a series of documents.

FRP composite girders(179,180)

- 2003. *Evaluation of the In-Service Performance of the Tom's Creek Bridge Fiber-Reinforced Polymer Superstructure*. Report VTRC 04-CR5. Richmond, VA: Virginia Department of Transportation.
- 2005. *Construction of a Virginia Short-Span Bridge with the Strongwell 36-Inch Double-Web I-Beam*. Report FHWA/VTRC 06-CR5. Richmond, VA: Virginia Department of Transportation.

FRP composite decks(181,182)

- 2007. *Development and Evaluation of an Adhesively Bonded Panel-to-Panel Joint for a Fiber-Reinforced Polymer Bridge Deck System*. Report FHWA/VTRC 07-CR14. Richmond, VA: Virginia Department of Transportation.
- 2009. *Rapid Replacement of Tangier Island Bridges Including Lightweight and Durable Fiber-Reinforced Polymer Deck Systems*. Report FHWA/VTRC 10-CR3. Richmond, VA: Virginia Department of Transportation.

GFRP bars(183-185)

- 2002. *Glass Fiber-Reinforced Polymer Bars as Top Mat Reinforcement for Bridge Decks*. Report VTRC 03-CR6. Richmond, VA: Virginia Department of Transportation.
- 2003. *Proof Testing a Bridge Deck Design with Glass Fiber Reinforced Polymer Bars as Top Mat of Reinforcement*. Report VTRC 03-R15. Richmond, VA: Virginia Department of Transportation.

- 2005. *Performance of a Bridge Deck with Glass Fiber Reinforced Polymer Bars as the Top Mat of Reinforcement*. Report FHWA/VTRC 05-CR24. Richmond, VA: Virginia Department of Transportation.

Hybrid Composite Beams (HCB)(186,187)

- 2017. *In-Service Performance Evaluation and Monitoring of a Hybrid Composite Beam Bridge System*. Report FHWA/VTRC 18-R5. Richmond, VA: Virginia Department of Transportation.
- 2018. *Full-Scale Laboratory Evaluation of Hybrid Composite Beams for Implementation in a Virginia Bridge*. Report VTRC 19-R3. Richmond, VA: Virginia Department of Transportation.

5.7 New York State DOT (NYDOT)

The New York Department of Transportation (NYDOT) has conducted a series of projects on the use of FRP composites ever since installing a complete FRP bridge superstructure in late 1998. From completed projects, NYDOT has developed design and long-term performance guidelines specifically for FRP decks and strengthening wraps. In particular, a hybrid FRP-concrete bridge deck system was recently studied by NYDOT. NYDOT has several relevant publications.

Whole FRP bridge decks(188-191)

- 2000. *Design, Fabrication, Construction, and Testing of an FRP Superstructure*. Report FHWA/NY/SR-00/134. Albany, NY: New York Department of Transportation.
- 2001. *Load Testing of an FRP Bridge Deck on a Truss Bridge*. Report FHWA/NY/SR-01/137. Albany, NY: New York Department of Transportation.
- 2004. *In-Service Performance of an FRP Superstructure*. Report FHWA/NY/SR-04/141. Albany, NY: New York Department of Transportation.
- 2007. *Dynamic Analysis of the Bentley Creek Bridge with FRP Deck*. Report FHWA/NY/SR-07/150. Albany, NY: New York Department of Transportation.

FRP strengthening wraps(192,193)

- 2001. *Strengthening of Route 378 Bridge Over Wynantskill Creek in New York Using FRP Laminates*. Report FHWA/NY/SR-01/135. Albany, NY: New York Department of Transportation.
- 2002. *Strengthening of Church Street Bridge Pier Capbeam Using Bonded FRP Composite Plates: Strengthening and Load Testing*. Report FHWA/NY/SR-02/138. Albany, NY: New York Department of Transportation.

Hybrid FRP-concrete decks(194,195)

- 2009. *Hybrid FRP-Concrete Bridge Deck System-Report I: Development and System Performance Validation*. Report C-02-07. Albany, NY: New York Department of Transportation.

- 2009. *Hybrid FRP-Concrete Bridge Deck System-Report II: Long Term Performance of Hybrid FRP-Concrete Bridge Deck System*. Report C-02-07. Albany, NY: New York Department of Transportation.

5.8 Oregon DOT (ODOT)

The Oregon Department of Transportation (ODOT) has performed several projects using conventional FRP composite systems in the form of externally bonded strengthening wraps and near-surface mounted FRP rebar. Recommendations on design, fabrication, and performance of these systems are suggested by ODOT and compared with the national specifications. Recently, ODOT has also studied the performance of the FRP composite decks and bolted connections between the composite decks and the steel girders. Information on ODOT projects and findings can be found in a series of reports.

FRP strengthening systems(196-199)

- 2000. *Testing of Full-Size Reinforced Concrete Beams Strengthened with FRP Composites: Experimental Results and Design Methods Verification*. Report FHWA-OR-RD-00-19. Salem, OR: Oregon Department of Transportation.
- 2006. *Capabilities of Diagonally-Cracked Girders Repaired with CFRP*. Report FHWA-OR-RD-06-16. Salem, OR: Oregon Department of Transportation.
- 2009. *Shear Repair Methods for Conventionally Reinforced Concrete Girders and Bent Caps*. Report FHWA-OR-RD-10-09. Salem, OR: Oregon Department of Transportation.
- 2012. *Strength and Durability of Near-Surface Mounted CFRP Bars for Shear Strengthening Reinforced Concrete Bridge Girders*. Report FHWA-OR-RD-12-12. Salem, OR: Oregon Department of Transportation.

Whole FRP composite decks(200)

- 2012. *Strength and Fatigue of Three Glass Fiber Reinforced Composite Bridge Decks with Mechanical Deck to Stringer Connections*. Report SR 500-490. Salem, OR: Oregon Department of Transportation.

5.9 Washington State DOT (WSDOT)

The Washington Department of Transportation (WSDOT) has performed a unique project involving dowel bars made of glass fiber reinforced polymers. The load transfer efficiency of the GFRP dowel bars was investigated and compared with the traditional steel dowel bars. Recommendations were made on the installation and performance of the GFRP dowel bars. In addition, WADOT has developed guidelines on using FRP wraps for seismic retrofitting of bridge columns.(201,202)

- 2012. *Glass Fiber Reinforced Polymer Dowel Bar Evaluation*. Report WA-RD 795.1. Olympia, WA: Washington Department of Transportation.

- 2010. *Seismic Retrofit of Cruciform-Shaped Columns in the Aurora Avenue Bridge Using FRP Wrapping*. Report WA-RD 753.1. Olympia, WA: Washington Department of Transportation.

5.10 Michigan DOT (MDOT)

The Michigan Department of Transportation (MDOT) supported a research project that looked into the development of guidelines for the design and use of externally-bonded FRP strengthening systems for Michigan bridges. International FRP-related guidelines were evaluated for their applicability to MDOTs needs. Also, experiments involving natural and accelerated aging were conducted to determine site-specific factors appropriate for Michigan. From the guideline review and test results, recommendations for design as well as installation, quality control, inspection, maintenance and repair were proposed.(203)

- 2014. *Design and Construction Guidelines for Strengthening Bridges using Fiber Reinforced Polymers (FRP)*. Report RC-1614. Lansing, MI: Michigan Department of Transportation.

CHAPTER 6. MATERIAL AND CONSTRUCTION GUIDELINES FOR COMPOSITE MATERIALS APPLICATIONS

This chapter presents guidance for the development of needed material and construction specifications when bidding and implementing a project using composite materials.

6.1 Overview

One of the great benefits of using composite materials for infrastructure applications is that they are a “designer” material. That is, by varying the fiber type and orientation, and resin type, their properties can be “designed” or changed for the application. This advantage is also a challenge for the designer as there is not set of standard material properties, nor a standard set of material handling and construction guidelines. To further complicate the matter, composites are produced and supplied by specific vendors, each of whom have products with their own set of properties and guidelines for the use and application of their products.

Therefore, in developing bid documents, specifications should provide a range of properties that have to be satisfied, and must provide the contractors who are conducting the repair with installation specifications that are consistent with the vendors own guidelines.

6.2 Typical Content of Guidelines

Many vendors have developed template documents that can assist the owner in both preparing bid documents for the project so that it can be constructed appropriately and does not have to be sole sourced. Items that are typically covered in these documents include:

1. Description of the bridge strengthening project
2. Materials proposed to be used including material data (dimensions, shelf life, strength/stiffness, strain to failure, fiber volume fraction, thermal resistance, etc.)
3. Construction
    a. Concrete repair: repair of defective reinforcement, restoration of concrete cross section, and cleaning and preparation all concrete surfaces prior to installing the FRP system
    b. Surface preparation: surface grinding, chamfering corners, grooves for near-surface mounted FRP system, surface profiling, and surface cleaning
    c. Installation of FRP system: shoring of repaired members, examining environmental conditions before and after installation of the FRP system
    d. Application of different FRP systems:
        1. Application of FRP systems:
            a. Application of wet lay-up FRP systems: mixing of resin components, primer and putty, saturant, applying fiber sheet and saturant, multi-ply fiber plies installation, overlapping, alignment of FRP materials, and anchoring of FRP sheets

    b. Application of PreCured FRP systems: application of adhesive, placement of procured system, grouting of procured shells
    c. Application of Near-Surface-Mounted FRP systems: application of embedding paste and placing FRP reinforcement
    d. Application of column wrap FRP systems in non-seismic application: FRP composite jacket or sleeves and continuous filament woven fabric
2. Curing:
    a. Methods to achieving proper cure (ambient temperature or rapid cure under elevated temperature)
    b. Time for full cure
    c. Temperature limits (minimum application temperature)
3. Protective coating and finishing: to protect the fibers from the elements, especially UV radiation and to give the final aesthetic effect.
4. Temporary protection: install temporary protection if needed
5. Inspection and quality assurance: inspection for debonding, inspection for adhesion, inspection for cured thickness, and auxiliary tests
6. Repair of defective work: repair of protective coating, epoxy injection of small defects, patching of minor defects, placement

As an example, the Sika Corporation has composite products that can be externally bonded to structural elements to increase strength and other products that can be used in NSM applications. For these products, they provide product data sheets, safety data sheets, and application guidelines.(204) These types of documents can be used to develop bid documents.

While guidelines for design and construction are more readily available, inspection and maintenance guidelines are not. This is an obvious target for future research and development.

CHAPTER 7. STATE DOTS FIELD IMPLEMENTATION OF BRIDGE STRENGTHENING TECHNIQUES USING COMPOSITE MATERIALS

This section summarizes the review of field implementations of new bridge strengthening methods using composite materials and the lessons learned from these projects. The lessons learned were gathered from reports from the Innovative Bridge Research and Construction Program and the Innovative Bridge Research and Deployment Programs (IBRC/IBRD) Program, surveys of members of the bridge community (including owners, bridge managers, and bridge designers), and information found in the literature. (9,205) A complete reporting of the results can be found in Tiera Rollins master's thesis.(3)

7.1 Summary of Applications

While there are certainly may projects involving bridge strengthening using composite materials outside of the IBRC/IBRD programs, that effort led to a significant number of novel projects. An overview of the IBRC program projects involving composite materials is given by J. M. Hooks.(205) A majority (about 85 percent) of the IBRC repair or strengthening projects involved FRP composites as the innovative technology. Of those projects, FRP sheet/plate bonding to increase flexural or shear strength were the most commonly employed methods. The other common application of composites was the use of FRP decks to reduce dead loads on the structure, thereby increasing live-load capacity. The following sections will summarize the laboratory studies, field implementations, and lessons learned for these three particular applications. Following this, general lessons learned by owners will be presented. Full details can be found in Tiera Rollins master's thesis.(3)

7.2 Flexural Strengthening with Composites

7.2.1 Laboratory Research and Key Findings

Externally bonded (EB) composites have been studied in the lab to investigate their ability to increase the flexural capacity of concrete beams, concrete slabs, timber beams, and steel beams.(206-220) The flexural strength of a beam can be increased by externally bonding or mechanically fastening FRP material to the tension face of the beam. The FRP material increases the cross-section of the member, which increases the moment of inertia and therefore the moment capacity. Sometimes the increase in cross-section can also increase the stiffness of the member, depending on the span length and the length and thickness of the repair material. The FRP material also provides an alternate load path, which increases the live load capacity of the member. The increase in total capacity is greater if the structure is jacked up before the composite is applied, so that the composite can also carry a portion of the dead load. However, one advantage of composite strengthening is the ability to apply the repair without closing traffic, which would not be an option if the structure is jacked up to remove dead load effects. Alternatively, the composite can be post-tensioned prior to applying it to the member, which will allow it to carry a portion of the dead load and thereby further increase the live load capacity of the structure. In cases where re-decking will occur, application of the repair prior to replacing the deck allows the FRP to help carry the new deck dead load.

From the research conducted, the following is a summary of key findings regarding flexural strengthening using composites:

- The concrete substrate should be repaired, and spalling and chloride ions removed, prior to strengthening to prevent further deterioration from these problems after strengthening.
- U-wraps can be used to provide additional anchorage, increase member stiffness, increase cracking moment, and allow the FRP to reach rupture without debonding (see figure 16).
- EB FRP can increase the ultimate capacity of concrete girders significantly without sacrificing the member's ductility.
- EB FRP can be used to strengthen one-way and two-way concrete slabs, by applying the FRP to the slab soffit in the form of strips and grid patterns, respectively (see figure 17).
- EB FRP can be used in conjunction with prestressed steel rods to produce a better result than one strengthening method alone, yielding a higher ultimate capacity while maintaining ductility and also improving serviceability (see figure 18).
- Prestressing can be directly applied to CFRP laminates, which can then be used to strengthen concrete girders or deck slabs while improving serviceability.
- Glass FRP can be used to successfully increase the flexural capacity of timber beams.
- In increasing flexural capacity of timber beams, EB FRP should only be applied to the tension face and not the compression face (see figure 19).
- Bi-directional FRP fabric can be used to increase flexural and shear capacity of a beam.
- "Mechanically fasted [MF] FRP strips were effective in developing composite action in slender [timber] beams in flexure and truss action in short deep beams."(217)
- The efficiency of MF FRP on timber beams was inversely related to the spacing of the fasteners.
- Steel beam failure is less ductile when the beam is retrofitted with composite materials. Research is being conducted to develop ductile anchorage systems for composite strengthening systems.
- Prestressing improves the strengthening effect of EB CFRP plates and steel FRP sheets used to strengthen steel girders.

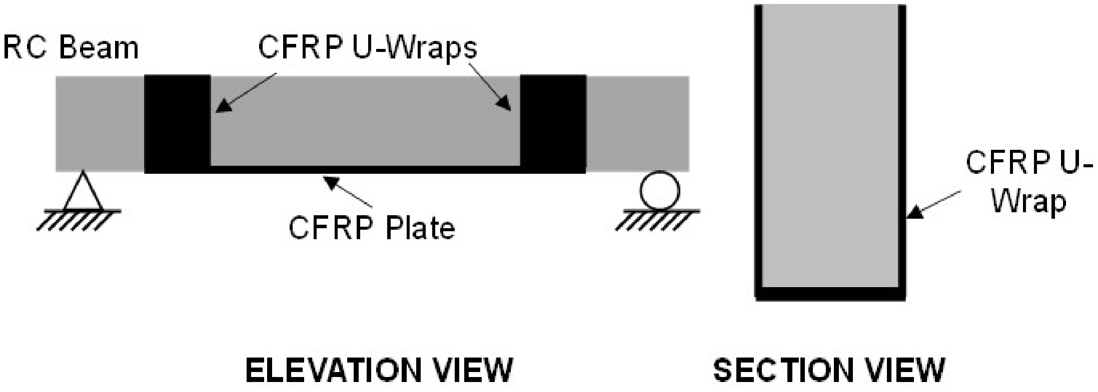

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Figure 16. Schematic of the application of U-wraps.

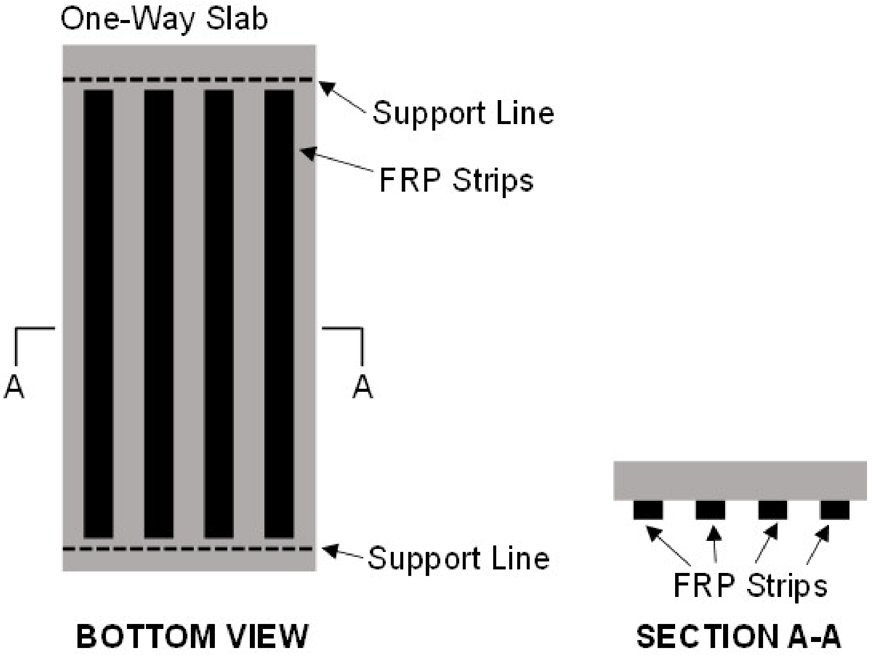

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Figure 17. Schematic of EB FRP used to strengthen slabs.

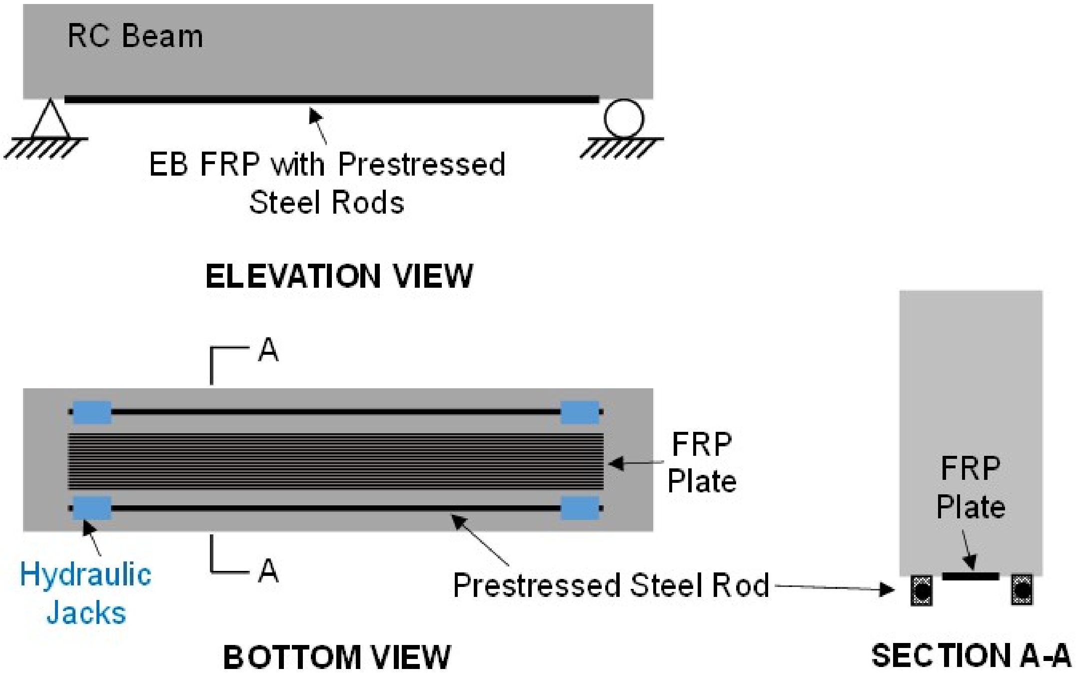

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Figure 18. Schematic of EB FRP used in conjunction with prestressed steel rods.

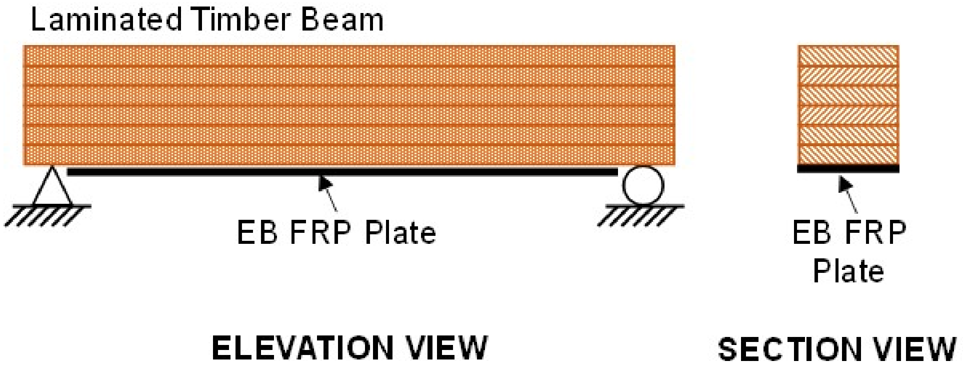

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Figure 19. Schematic of EB FRP used to increase flexural capacity of timber beams.

7.2.2 Field Implementations

Hundreds of structures around the world have been strengthened in flexure through the use of FRP composites.(221-249) Many installations date back to the 1980's.(3) Through the IBRC program alone, the following types of structural members have been strengthened in flexure:

concrete T-beams, prestressed bulb-T-beams, arch bridges, concrete box beams, and steel plate girders.(9)

Some advantages of rehabilitating flexural bridge members with composite materials were discovered through the IBRC/IBRD programs.(9) Most of the strengthening was accomplished using EB FRP. FRPs are lightweight and can be installed quickly and easily without heavy lifting equipment. As few as two people can install pre-cured FRP plates, making this strengthening technique ideal for projects with limited manpower, such as those owned by county agencies. Traffic can be left open during the bonding process, but closing traffic may lead to a stronger bond. The epoxy bond takes a matter of hours to cure to full strength before traffic can be opened. This time frame is much shorter than what is needed for other types of repairs.

Some disadvantages and challenges associated with using EB FRP were encountered during the IBRC/IBRD installations.(9) The bonding process was reported to be messy and ruin application tools. However, procedures have been developed and, if followed, can minimize the messiness. Since the technology was new, some states had difficulties installing the material properly, leading to longer than anticipated installation times and less than ideal final products (with air bubbles or peeling). Training materials have been developed to prevent installation difficulties in the future. Several states reported that FRP materials are more expensive than concrete or steel. However, the service life they provide, when installed correctly, far outweighs the initial cost, making them a cost-effective alternative for long-term repairs. Finally, costs of new materials are typically greatly reduced once the new materials become more mainstream in the industry and specifications are published to eliminate the proprietary nature of the material.

Another discovery was that FRPs are susceptible to ultraviolet deterioration, so it is recommended that the material can be coated by the manufacturer for protection from UV rays. Shear stresses can cause the material to delaminate or peel at the edges, and determining adequate anchorage requirements is difficult. Extensive research has been conducted to address these drawbacks.

Some more general lessons learned by the IBRC/IBRD projects have also been documented.(9) The most significant factor in the success of external FRP bonding is proper surface preparation. The surface needs to be cleaned and textured to ensure a good bond between the member and the FRP material. If the surface is not properly prepared then the FRP may delaminate which will lead to a loss in strength. When using externally bonded plates, care should be taken in the design so that joints connecting adjacent plates are not placed at maximum moment locations. The joints may be vulnerable to delamination under large strains. Special care must also be taken to ensure that galvanic induced corrosion does not occur between a steel girder and carbon fibers. When FRP wraps or sheets are used on steel girders, the design should not encase the bottom flange because it will trap water and salts. Extra layers of FRP on the bottom flange to achieve a certain increase in strength are preferable to layers of FRP on the side of the web. A combined system of adhesively-bonded and mechanically fastened plates provides the most reliable strengthening procedure.

7.3 Shear Strengthening with Composites

7.3.1 Laboratory Research and Key Findings

Similar to flexural strengthening with EB FRP, EB FRP can be used to strengthen structures in shear, including FRP sheets or strips, U-shaped stirrups, L-shaped plates, near surface mounted (NSM) laminates or NSM rods, and shear spikes.(256,250,37,40,251)

Many laboratory experiments have been conducted on the shear behavior of RC beams strengthened with FRP composites. (252-264) A compilation of lessons learned from experimental research in the UK has also been published.(71) "Shear strengthening is affected by the size of the beam being treated and debonding and strain checks need to be made. The use of FRP bars glued into drilled holes in the web of a beam adds substantial shear strength."(71)

7.3.2 Field Implementations

Numerous authors have documents field implementations of shear strengthening with FRP materials on bridge girders, bridge columns, and concrete deck slabs.(225,226,235,244,247,265,266-274) Bridge girders which have been strengthened in shear include concrete T-beams, channel beams, prestressed girders, and timber beams. FRP materials can also be used to strengthen a member in flexure and shear at the same time.

The following is a summary of key findings regarding shear strengthening using composites that have come from both the laboratory work and the field installations:

- CFRP grid sections can be installed vertically in concrete deck slabs to change the failure mode from shear to flexure (see figure 20).
- CFRP plates can be bonded to slab soffits to increase shear capacity.
- FRP double-headed shear bars provide excellent shear reinforcement, good fatigue performance, and are easy to install in shallow concrete members (see figure 21).
- EB FRP stirrups can be used to strengthen bridges that were designed without internal shear reinforcement, but implanting shear bars is a more effective strengthening method.
- U-wraps can increase shear capacity and deformation capacity of a beam, but the new governing failure mode is debonding of the U-wrap.
- The application of vertical strips with a horizontal anchoring strip was found to be the most effective shear strengthening system orientation for RC girders (see figure 22).
- When using a full wrap to strengthen a girder in shear, it is recommended that the wrap be left unbonded on the sides of the beam, because it will yield a greater increase in shear strength, than if it were fully bonded.

- Dynamic debonding and deformation from the movement of a composite strengthening system on either side of a shear crack can cause the composite to fail at lower strains than the failure strain of tensile coupons.

- Partial or full embedment of L-shaped CFRP stirrups is more effective than EB FRP in shear strengthening (see figure 23).

- Load testing of a bridge should be conducted prior to strengthening, because capacity calculations based on strengthening codes can vary from the actual capacity.

- The embedded through-section (ETS) method is a new shear strengthening method that relies on the core of the beam which provides a better bond than EB or NSM (see figure 24).

- Diagonal layup of EB FRP sheets is more effective than vertical layup when strengthening timber beams in shear (see figure 25).

  Shear spike fiberglass rods are effective in strengthening timber railroad bridge ties in shear.

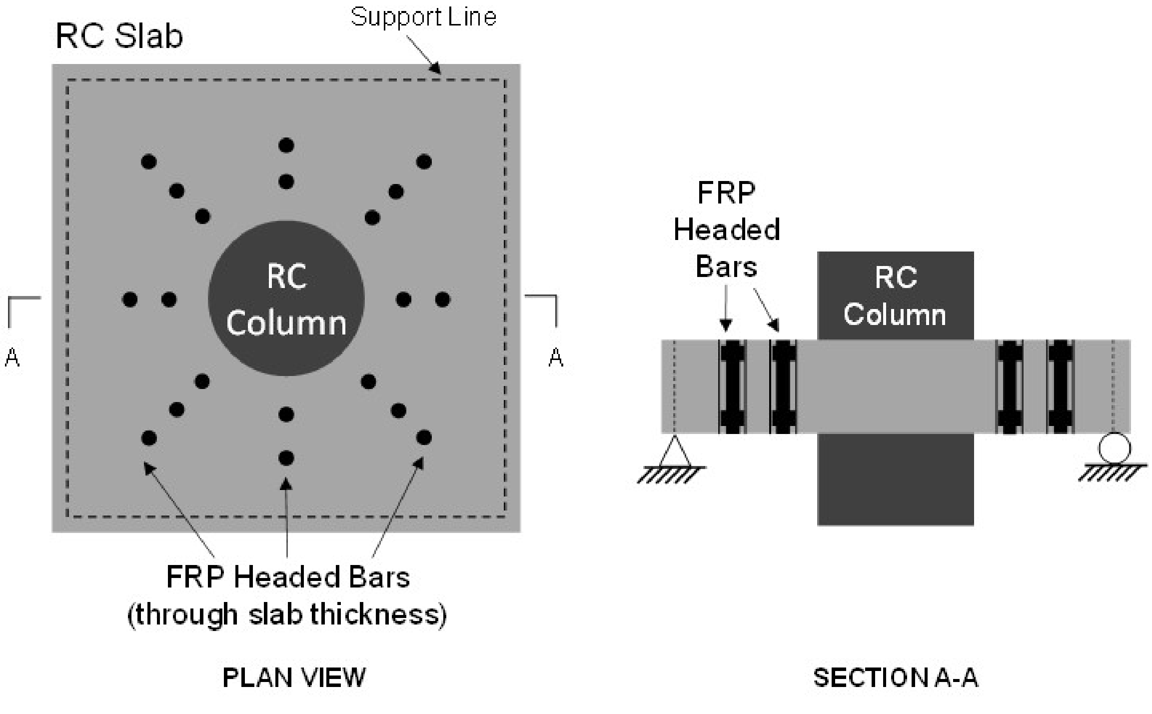

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Figure 20. Schematic of vertically installed CFRP grid sections.

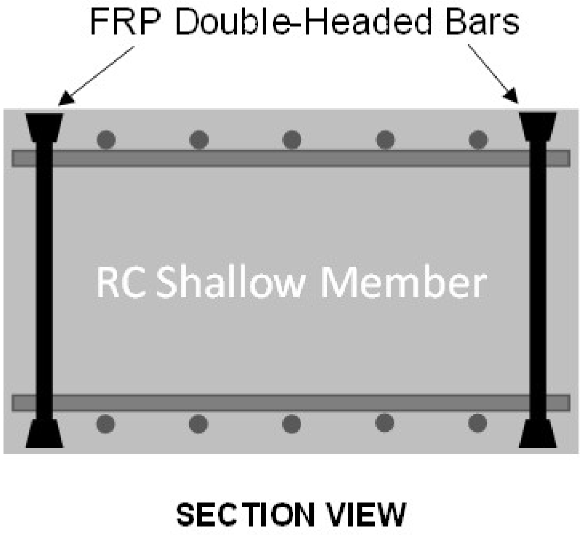

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Figure 21. Schematic of FRP double-headed shear bars to provide shear reinforcement.

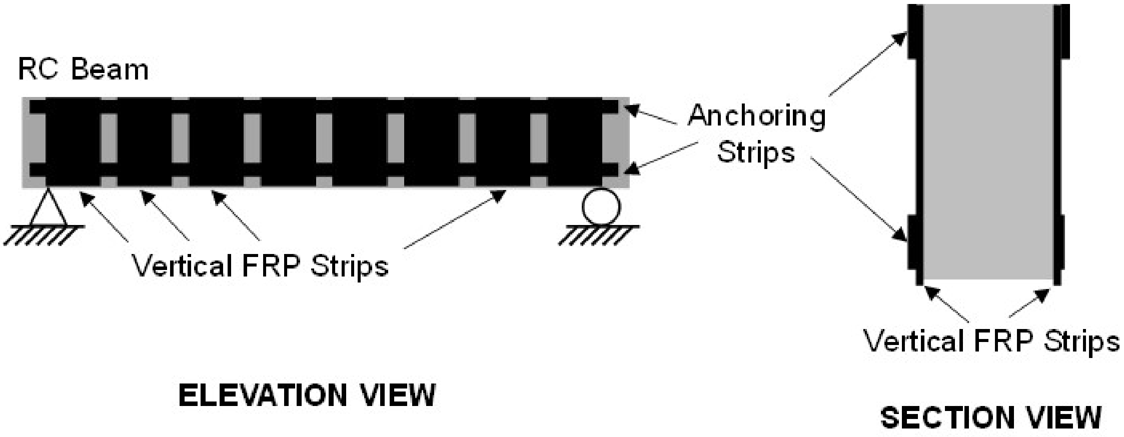

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Figure 22. Schematic of vertical strips with a horizontal anchoring strip.

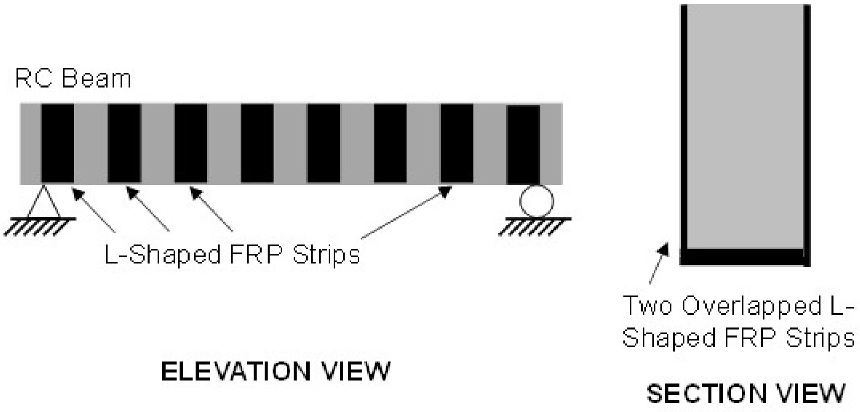

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Figure 23. Schematic of embedded L-shaped CFRP stirrups used for shear strengthening.

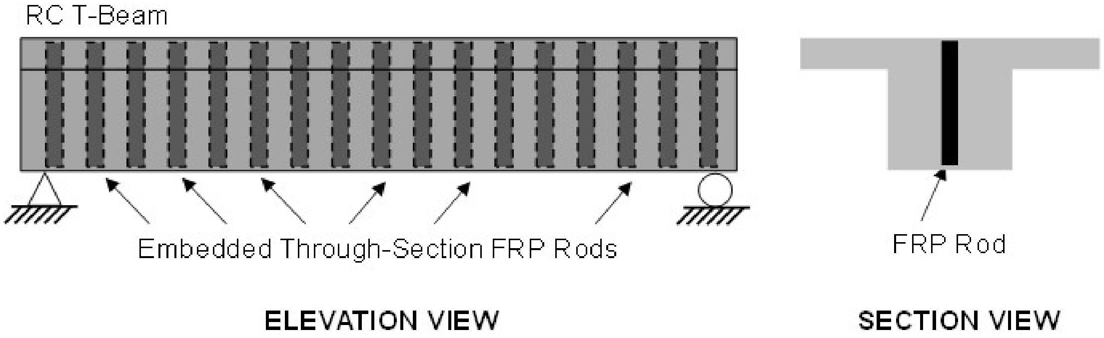

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Figure 24. Schematic of the embedded through-section method of shear strengthening.

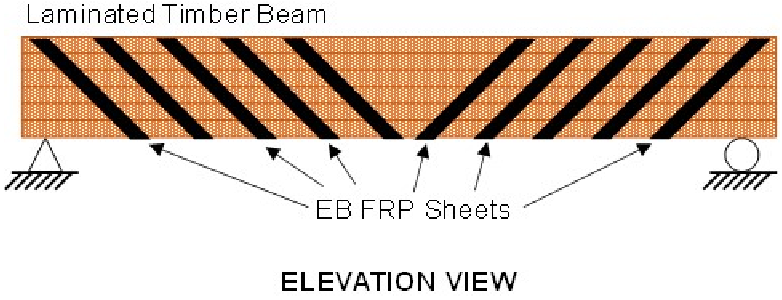

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Figure 25. Schematic of the diagonal layup of EB FRP sheets for shear strengthening of timber beams.

7.4 Lightweight FRP Decks

FRP deck panels offer many benefits over traditional decks and considerable research and resulting implementation of them has taken place.(235,245,275-314) “As compared with cast-in-place concrete bridges [sic] decks, they weigh 80 percent less, can be erected twice as fast and have service lives that may be two to three times greater.”(282) They can be erected so quickly because the panels are prefabricated, which means no framework is required. Rebar is also not needed, which reduces the cost and construction time of the project. Heavy lifting equipment is not required for the construction because the panels are so lightweight. The dead load of the structure is greatly reduced, which increases the structure’s live load capacity. The FRP panels can carry load immediately after being installed, whereas concrete has to cure for several days before opening to traffic. The absence of heavy lifting equipment and shorter road closure times also decrease the cost of the project. The FRP panels are not prone to salt damage like concrete decks and are more resilient in adverse environments, which means lower maintenance costs over the service life of the bridge. Overall, FRP deck panels offer an economic alternative to traditional concrete decks.

FRP deck panels also offer benefits over open steel grid decks. They are just as lightweight, but they are corrosion resistant. They allow for collection of storm water runoff, bike use on the roadway portion of the bridge, and protection of sub deck elements from the weather. Due to the layer of overlay on FRP decks, the resulting roadway surface offers better rideability than open steel grid decks.

There are several different types of FRP decks. One difference between deck types is the core configuration which can be honeycomb sandwich, solid core sandwich, or pultruded hollow core sandwich.(281) The composite materials used to construct the decks can also vary.

Many composite decks have been installed on bridges around the world, some for newly constructed bridges, and others for replacing deteriorated concrete decks of existing bridges while increasing the live load capacity due to the lightweight feature of composite decks. In other applications, bridge decks that were cracked or damaged have been repaired and strengthened using composite materials.

A complete review of the research results and field installations can be found in Tiera Rollins master’s thesis.(3)

7.4.1 Lessons Learned

This section covers field lessons learned and discusses issues that have been observed during or after the installation of lightweight decks. Much of the lessons were drawn from the information collected from deck projects that were part of the IBRC program.(9)

The following is a summary of key findings regarding lightweight decks:

- Aluminum bridge decks are expensive and may be limited to use on steel girder bridges in congested areas.

- Construction workers should be trained to lift and place aluminum deck panels and should conduct practice runs before installation of the panels.

- Sandwich plate system deck panels should be small enough to minimize fit-up problems in the field and minimize weld-induced distortion.

- Proper overlays still need to be identified for SPS decks.

- It is crucial to have sufficiently flexible wearing surface and bonded joints for FRP decks, especially on moving bridges.

- FRP surface shifting during fabrication of FRP-wrapped balsa wood bridge led to insufficient infusion of epoxy which caused delamination.

- Foam cores are not recommended for FRP decks.

- Drain holes should be drilled in FRP decks at the time of installation to prevent water damage.

- Two-part epoxy-coated screws were used to successfully reattach the tubes of a GFRP deck to the top plate after they delaminated.

- An FRP fabric wrap can be used to repair a delaminated GFRP honeycomb deck.

- Lateral load distribution between the tubes in an FRP tube deck panel was found to be inefficient on the Chief Joseph Dam Bridge in Bridgeport, WA.

- The soft core of GFRP panels can reduce the effective bending width by 25 percent compared to a homogeneous isotropic panel.

- FRP-glulam panels are more ductile than glulam panels and have a 35.7 percent higher failure load.

- FRP deck design can be modified to accommodate roadway skew and crown, and attachment of the deck panels to the bridge framing system.

- So far, full composite action has been shown to be difficult to achieve with an FRP deck on steel or concrete girders.

- FRP cellular decks exhibit linear-elastic behavior up to design service load and has average deflection of L/664.

7.5 General Input from Bridge Owners

When surveying bridge owners, their comments aligned well with many of the lessons already mentioned. Their observations are as follow:

- FRP installations can be very expensive, but they also offer a much longer service life than traditional materials. The long-term savings in maintenance should offset the higher initial costs when comparing FRP materials to traditional steel and concrete.

- It is essential to have a manufacturer representative on site to ensure successful installation of the material.

- FRP solutions need to be designed on a case by case basis for the specific application.

- The effectiveness of the repair is directly related to the soundness of the substrate it is bonded to. In the case of concrete applications, the strengthening only works to its full extent if the concrete surface is in good condition (not spalling).

- A caution is given in that strengthening a bridge does not always increase its live load capacity if only a portion of the bridge is being patched or repaired. Analyses should always be run to verify that the strengthening repair will increase the live load capacity of the entire structure before allowing heavier traffic.

- When using FRPs for strengthening, one should also consider the service limit state. A recommendation was given that the structure should be jacked before repair so that the FRP material can arrest cracks due to service loads as well as increase the maximum capacity. However, jacking the structure requires road closure that may otherwise be unnecessary for a composite retrofit.

- West Virginia reported that it had difficulty successfully implementing FRP decks, but that FRP wraps work “fairly well.”

- Many survey participants reported the need for guidelines and codes for FRP repairs. The lack of specifications for design and lack of guidelines for maintenance and inspection after installation were concerns mentioned numerous times in the survey results.

- Others commented that manufacturing support is needed to standardize material properties of FRP materials, as they are currently proprietary. This standardization may lower the cost of FRPs.

- Another major concern was lack of training. A knowledgeable workforce is needed for design of the FRP repair, installation of the FRP repair, and the maintenance and inspection of the repairs. Training is needed for State organizations before FRP repairs will become more widely used.

- Inspection of FRP repairs was reported as extremely difficult.

- Finally, the need for promotion of FRP repair methods was reported as necessary to make them more mainstream.

CHAPTER 8. DESIGN EXAMPLES OF BRIDGE STRENGTHENING TECHNIQUES

In order to provide designers with examples of repair techniques, four new design examples were created (using traditional materials) and three existing representative design examples were identified (using composite materials).

8.1 Examples Using Traditional Materials

The four examples of bridge strengthening methods using traditional materials that were developed represent a range of common applications that include (1) steel truss member strengthening, (2) steel plate girder shear and flexural strengthening, (3) stringer retrofit – composite action and continuity changes, and (4) concrete pier cap strengthening.

The steel truss member strengthening design example involves the addition of steel cover plates to steel truss members, one-tension member and one-compression member. The bridge is strengthened to meet HL-93 design loading (the existing bridge was designed for a HS-15 live load). This example is based on AASHTO LRFD Bridge Design Specifications, 7th Edition and can be found in Report No. FHWA-HIF-18-042.(315)

The steel plate girder shear and flexural strengthening design example involves the addition of steel strengthening material to an existing steel plate girder. The existing bridge was designed for HS-20 live loading. The girder is to be strengthened due to section loss from corrosion. The design objective is to strengthen the girder to obtain a HS-20 live load rating factor equal to or greater than 1.0. This example is based on AASHTO LRFD Bridge Design Specifications, 7th Edition and can be found in Report No. FHWA-HIF-18-043.(316)

The stringer retrofit – composite action and continuity changes design example involves the replacement of stringers during re-decking on an existing truss/floorbeam/stringer bridge. The existing stringers are non-composite rolled W24x76 beams, that were designed for HS-20 live loads. The design objective is to provide new stringers to obtain a HS-25 live load rating factor equal to or greater than 1.0, while minimizing the weight of the new stringers. The flexural live load ratings of the new stringers were significantly increased by both making the stringers composite with the new deck and changing the continuity of the stringer spans. This example only involves a study of the flexural resistance of a typical interior span for the new and existing stringers using the Strength-I Limit State. This example is based on AASHTO LRFD Bridge Design Specifications, 7th Edition and can be found in Report No. FHWA-HIF-18-044.(317)

The concrete pier cap strengthening design example involves the addition of external post-tensioning bars to a concrete pier cap. The bridge is strengthened to carry a HL-93 design live load. The existing bridge was designed for a H-15 live load, and the previous widening was designed for a HS-15 live load. This example is based on AASHTO LRFD Bridge Design Specifications, 7th Edition and can be found in Report No. FHWA-HIF-18-045.(318)

8.2 Examples Using Composite Materials

Three very thorough and representative examples of bridge strengthening methods using composite materials can be found in the literature and include (1) externally bonded FRP: flexural strengthening of a concrete girder, (2) externally bonded FRP: shear strengthening of a concrete girder, and (3) near surface mounted FRP: flexural strengthening of concrete girder.

The externally bonded FRP: flexural strengthening of a concrete girder design example illustrates the flexural strengthening of a reinforced concrete T-beam using an externally bonded carbon fiber-reinforced polymeric reinforcement system to accommodate higher loading. This design example, found in NCHRP Report 655, is based on the Guide Specifications from NCHRP Report 655 and the AASHTO LRFD Bridge Design Specifications, 7th Edition. (319,131)

The externally bonded FRP: shear strengthening of a concrete girder design example illustrates the shear strengthening of a reinforced concrete T-beam with an externally bonded carbon fiber-reinforced polymeric composite U-jacket system to accommodate higher loading. This design example, found in NCHRP Report 655, is based on the Guide Specifications from NCHRP Report 655 and the AASHTO LRFD Bridge Design Specifications, 7th Edition. (319,131)

The near surface mounted FRP: flexural strengthening of concrete girder design example illustrates the flexural strengthening of a reinforced concrete beam using a near surface mounted (NSM) fiber reinforced polymeric reinforcement system to accommodate higher loading. This design example, found in ACI 440.2R-08: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures is based on ACI 318 and the ACI 440.2R-08 Specifications. (134,143)

CHAPTER 9. CONCLUSIONS

This chapter provides a summary of the work done, as well as recommendations for future work.

9.1 Summary

With the high demand for cost efficient, fast, and long-lasting rehabilitation methods for our nation's deteriorating infrastructure, new materials and strengthening methods are being developed all the time. This report provides a summary of the findings of Task 6: Report on Techniques for Bridge Strengthening, one task performed under Project Award: DTFH61-11-H-00027: Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance. Additional details regarding the Task 6 effort can be found in Tiera Rollins master's thesis.(3) The primary focus of the work was to provide an update, beyond the 1997 synthesis report, on emerging methods of bridge strengthening.(1)

To this end, it has been found that the vast majority of new strengthening methods involve applications if composite materials including (1) externally bonding FRP, (2) near-surface-mounting FRP, (3) post-tensioning of FRPs, (4) fiber reinforced cementitious matrix as a strengthening system, (5) spray FRP as a strengthening system, and (6) column retrofitting with FRPs. As these new methods have evolved, and as numerous projects have been implemented in the field, new design and construction criteria and specifications have also been developed.

In addition to applications of composite materials, designers are also identifying new ways to utilize traditional materials for increase the capacity of bridges. This includes applications of post-tensioning, converting simple span bridges to continuous bridges, and converting non-integral abutment bridges to integral abutment bridges.

9.2 Recommendations for Future Work

While significant advances have been made in both the methods and materials being used to strengthen bridges over the past twenty years, additional advances are needed to make the techniques more easily and widely adopted. In conducting this work, several other areas of future work have also come to light. The following are areas that would be beneficial to expand upon.

- Whether a repair is using traditional or new materials, there is always an opportunity to make the construction process more affordable and to have less disruption on the travelling public during the process.
- There is an ongoing need for completely new repair concepts to be developed. For example, two of the more recent concepts that have been introduced include turning simple spans into continuous spans and making non-integral abutment bridges into integral abutment bridges.
- In terms of materials, while composites have entered the arena as an option, other new or improved materials will surely follow. One material that is quickly finding its way into bridge applications is Ultra High Performance Concrete (UHPC). This material has great promise both for new construction, and for bridge strengthening.

- For new strengthening procedures, it is important that the costs of the applications be documented so that other potential users can conveniently compare costs to those associated with more traditional methods. With so many applications of composites now in place, a project that solely looks at the associated costs would be very valuable. In doing this, it is important that (1) the material cost versus the construction costs be documented as composites tend to have high material costs but low installation costs be studied, and (2) life-cycle costs be considered as composite materials often have higher initial costs, but may well have lower life-cycle costs due to their durability in harsh environments.
- There have been considerable advances made in developing design codes for composite strengthening procedures, but there is little standardization of material specifications and construction guidelines. This is natural as composite materials are producer specific, but any work that can be done to move toward standardizations will help a more widespread adoption of these composite strengthening applications to occur.
- A guide that tabulates all of the existing composite manufacturers and their various strengthening products and related applications would be very helpful.
- When new materials are used, there is an important need for associated inspection and maintenance guidelines to be developed. Even today, many DOT’s are using traditional inspection methods to evaluate composite applications. While much work has been done in this area, further work is needed to transition affordable and efficient inspection methods into practice.
- Finally, the study and documentation of the performance of a wide range of composite repairs across the country would be very beneficial. The earliest of these repairs are now more than twenty years old, and it is very important that we learn from the successes and failures.

Finally, it is recommended that the creation of a web-based resource site that can become a living repository for bridge strengthening information be considered. The motivation behind the creation of a bridge strengthening website framework would be to gather information on existing and evolving bridge strengthening methods in one place, and on an ongoing basis, and make it accessible to the public. This would provide a valuable resource for bridge owners and bridge engineers which would allow them to stay up-to-date on leading edge technologies available in the field and allow them to choose appropriate methods for their projects.

As part of the work done for Task 6, the research team developed and proposed a framework for such a web-based resource site.(3) The work included a proposed website framework and included a flowchart, example pages for each level of the website, a list of traditional and innovative bridge strengthening and repair methods, a maturity rating system, and a case study submittal template.(3) The flowchart demonstrated how pages of the website could be navigated, and can serve as a development tool along with the example pages for a fully functional website. The technology information page of the website offers various PDFs to the user, including technology information, photos, case studies, a design example, and a bibliography. Example PDFs were created for each of these pages. The list of bridge rehabilitation methods can expand as new technologies and methods are developed. A maturity rating system was developed that allows the user to distinguish between traditional methods and new technologies. A case study submittal template was proposed that can be downloaded, filled out by users, and uploaded to add their project information to the website.

A major function of the proposed website is to allow users (primarily government agencies) to contribute case studies, photos, and technical information on new methods being used in the field. When a new rehabilitation method becomes successful in one region of the country, case studies can be uploaded to this website to showcase the success and generate interest in the new technology. The website would provide a much more efficient means of gathering and distributing new information than creating synthesis reports every decade or two, as has been done in the past. If the website is fully developed and utilized, it can be continually updated by the users and, if desired, synthesis reports will be much easier to create, as most of the relevant information will be in one place.

An analogous website for bridge preservation currently exists and is hosted by the Transportation System Preservation - Technical Services Program (TSP-2). That site, which has “Pavement Preservation” and “Bridge Preservation” buttons, was created by AASHTO as an “efficient means to disseminate information to AASHTO member agencies for preserving their highway infrastructure.” It is proposed that a bridge strengthening website be considered for addition to this site by adding a “Bridge Strengthening” option.(3)

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