NEW AND EMERGING METHODS OF
BRIDGE STRENGTHENING AND REPAIR
AND DEVELOPMENT OF
A BRIDGE REHABILITATION WEBSITE FRAMEWORK

by

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ABSTRACT

The purpose of this thesis is to document state-of-the-art methods for bridge strengthening and to develop a framework for a bridge rehabilitation website that will be a repository for information on new strengthening methods and will make this information available along with information on traditional strengthening methods. The last comprehensive state-of-the-art report on bridge strengthening was published in 1997. Through an in-depth literature review, new and emerging methods of bridge repair developed since 1997 are presented. Based on the current bridge strengthening and repair methods, a framework for a bridge rehabilitation website is created which enables bridge owners and bridge engineers to efficiently select appropriate rehabilitation methods for their bridges. The website framework presents traditional and novel repair methods highlighting the applicability of each method depending on bridge type, and allows the user to access case studies, photo galleries, and design examples of various repair options. The website framework also allows users to contribute case studies of their bridge strengthening projects, which will enable the site to be continually updated.

Chapter 1

INTRODUCTION

1.1 Research Problem Statement

The nation's population and economy are growing, which puts larger stresses on the nation's aging and deteriorating infrastructure. The transportation system built decades ago needs to be updated in order to support the increase in demand, so bridge owners and bridge engineers are looking for efficient methods to repair their bridges and increase their live load capacity. These methods not only need to be cost effective and quickly implementable, but they also need to produce long term solutions which will lengthen the service life of the structure. New methods have been and are being developed to meet these criteria. In order to make information on the new and emerging technologies more readily available to bridge owners and bridge engineers, the information needs to be gathered together for easy access.

1.2 Research Objectives

The first research objective is to synthesize a report which details the new bridge repair methods which have been developed since the last comprehensive bridge report in 1997 [1]. The second research objective is to create a framework for a website about traditional and novel bridge repair methods, featuring a decision matrix which enables bridge owners and bridge engineers to more efficiently select appropriate repair methods for their bridges.

1.3 Scope of Investigation

The new and emerging technologies being used for bridge repair were identified through an exhaustive 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.

The website framework consists of a decision matrix, a Technology Submittal Form template, and a Technology Information page template. The Technology Information page includes general information, photos, case histories, and a design example.

1.4 Research Approach

To collect information on new strengthening methods, an exhaustive literature review was conducted using the databases Web of Science, Compendex (Engineering Village), ASCE, and TRID. Surveys were sent out to members of different AASHTO, FHWA, and TRB committees and teams in the spring of 2015. This literature search was not meant to yield a comprehensive listing 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. Chapter 2 will present a broad range of research topics related to bridge strengthening, while Chapter 3 will present representative examples of field implementations of new bridge strengthening methods and the lessons learned from those implementations.

To assist in the development of a website framework, other web-based decision guides were researched and used as models for the framework of the bridge rehabilitation website and design examples found in the literature were investigated and one particular example was adapted to create a template for the website.

Chapter 2

LITERATURE REVIEW: LABORATORY RESEARCH CONCERNING BRIDGE STRENGTHENING

2.1 Literature Review Overview

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. Since traditional methods of strengthening, listed in Appendix A.1, are described and expounded upon in previous NCHRP synthesis Reports 249 (1997) [1] and 293 (1987) [2], this report focuses only on new methods and variations of traditional methods developed since the 1997 synthesis. Most of the research and new methods that have been applied in the field according to the literature review, IBRC reports, and survey results involve composite materials. Findings from the literature review and IBRC reports will be described throughout this chapter and Chapter 3. The survey results can be found in Section 3.2.

The literature review conducted included the databases Web of Science, Compendex, ASCE, and TRID. About 87% of the reports and papers found involved applications of advanced composite materials (ACM) in the strengthening procedure. 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. Throughout the remainder of this thesis, these programs will be referenced collectively as the 'IBRC program' or 'IBRC projects.' Reports were collected from the states which detailed lessons learned from their experiences and compiled into a report which remains unpublished at this time [3]. The IBRC reports were reviewed as part of the literature search for this project. About 85% of the IBRC repair or strengthening projects involved fiber reinforced polymer (FRP) composites as the innovative technology.

Composites have been implemented in a variety of strengthening methods including reducing dead load, strengthening of members, and post-tensioning of members. An overview of composite materials will be given, followed by backgrounds and definitions of the new bridge strengthening methods. The remainder of this chapter will present the laboratory research findings reported in the literature review. While some research topics covered in this chapter are not bridge strengthening methods, they were included in order to provide valuable information related to bridge strengthening. As previously stated, the information presented in this document provides a representative sample of the research and activities that have been conducted on new methods of bridge strengthening and is not meant to be an all-inclusive account of completed projects.

2.2 Composite Material Overview

Composites materials provide great benefits for bridge repair because they have a high strength-to-weight ratio, which makes them lightweight, and they are durable because they do not corrode like steel or deteriorate under water exposure like concrete. Composites are made up of textile fibers in a polymer matrix, thus they are known as fiber reinforced polymers (FRPs). Fibers most commonly used for structural applications include carbon (graphite) and E-glass (fiberglass). Some research has been conducted with Kevlar (aramid) fibers [4]. A study was conducted to compare these materials and the results showed that all three provide adequate strength, and therefore the limiting factor would be cost of material and the amount of reinforcement required [5]. The polymer matrix used is commonly an epoxy resin.

The fibers can be oriented in a single direction (unidirectional), or in two or more directions depending on the application and desired strength. Unidirectional fibers perform best in tension because they can be aligned with the axial stresses, while fibers that cross at varying angles perform well in shear. The fibers are most commonly woven into sheets for structural applications. The fabric sheets can be applied to the structure in situ, which means irregular geometries can be accommodated. The segment of the structure in need of repair can be wrapped in the fabric and then epoxy is applied which will harden and form a bond between the original structure and the composite. Mechanical fasteners can also be used to install FRP as an alternative to epoxy bonding. Premade panels can be ordered from a manufacturer to reduce installation time for flat surfaces. FRP bars are also available for near surface mounted (NSM) or post-tensioning repairs.

Composites are lightweight, so they are less expensive to transport than steel or concrete and easier to handle and install (no heavy construction equipment required). A summary of the applicability of FRP in civil engineering structures is given by Meier [6]. The advantages of composites in structural strengthening to increase flexural capacity, and improve shear and impact resistance are outlined by Berry [7]. He explains that increased legal loads of modern day require many buildings and bridges built decades ago to be strengthened.

2.3 New Bridge Strengthening Methods: Backgrounds and Definitions

This section offers descriptions, advantages and disadvantages of the new methods which have been developed since the 1997 synthesis report. These methods include external bonding, mechanical fastening, near surface mounting, and post-tensioning of FRPs. Fiber reinforced cementitious matrix and spray FRP as strengthening systems are also introduced. Research conducted to develop and improve these methods is covered in Section 2.4.

2.3.1 Externally bonded FRP

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy, so it is also called epoxy bonding in the literature. 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 may even remain open during repairs [8].

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 (see Section 2.6.5 for more details).

Externally bonded (EB) FRPs provide an alternate load path for the structure, which increases the structural capacity. EB FRPs 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 to strengthen columns in flexure, shear, and axial strength, and to provide added impact resistance which will be discussed in Section 2.5.3. Research is ongoing to extend the application of EB FRP to fatigue repair and strengthening (Section 2.5.2) and strengthening torsional members (Section 2.5.5).

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 delaminations 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.

2.3.2 Mechanically fastened FRP

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 (see Section 2.4.1). 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.

2.3.3 Near surface mounting composites

Another method utilized to minimize debonding is near surface mounting. This method involves cutting a groove in the surface of the beam, applying epoxy, placing the FRP material, and filling the remaining space with epoxy. “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” [9]. The grooves can be cut longitudinally, vertically, or diagonally on the beam 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.

2.3.4 Post-tensioning composites

Post-tensioning is not a new method, but it can be applied to all of the new methods listed above. Post-tensioning introduces a tensile axial 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. 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 capacity.

2.3.5 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" [10]. 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 bond the system to the structure. 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 unvarying workability between 40 and 105 degrees F [11]. 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 the reinforcing of FRCM, but steel fiber sheets are also being researched (see Section 2.4.4).

2.3.6 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 concrete to be repaired resulting in a 2-dimensional random distribution of fibers applied to the surface of the structure [12].

2.4 Experimental Research of New Bridge Strengthening Methods

Most of the material found in the literature review consisted of experimental studies on composite materials used to strengthen bridges and other structures. Since the concept of strengthening civil structures with composite materials is new, significant research has been, and continues to be, conducted to provide a database of how the materials perform in different circumstances. The research conducted has created the needed stepping stones to enable composite repairs to become a more mainstream technique and to provide a foundation for future field implementation.

The experimental studies presented in this section investigate how to improve new bridge strengthening methods. Tests were conducted to develop stronger bonds, better anchorage systems, and optimal material compositions to maximize the benefit of retrofitting with composite materials. Using a combination of methods simultaneously to achieve greater increase in structural capacity was also researched in several studies.

2.4.1 Anchorage systems for EB and MF composite retrofits

Initially, FRPs were simply applied to the surface of the beams to restore lost capacity. However, considerable research and testing has been conducted to improve the strength gained from composite repairs. One major area of concern and research has been to prevent bond delamination. Debonding of the composite material from the concrete substrate is a major concern, as it compromises the effectiveness of the repair. Various techniques to improve the bond have been researched.

Traditional surface preparation techniques, such as sandblasting, are compared to an alternative technique of grooving the surface, proposed in reference [13] from 2010. “Surface preparation is typically associated with such constraints as adverse environmental impacts, economic losses due to stoppage of activities, repair costs, or even inaccessibility of the member(s) to be strengthened” [13]. A study conducted in

2007 on the effect of concrete surface profile on bond strength of FRP reported that surface roughness achieved with grinding or pressure washing appeared to have no significant influence on the overall performance or failure mode of the FRP [14]. However, the 2010 study on the effects of grooving beam surfaces reported that "Results indicated that surface preparation prior to bonding of FRP sheets increased ultimate rupture strength. It was also found that the substitute preparation methods greatly compensated for the lack of conventional surface preparation such that they changed, in some cases, the ultimate failure behavior of the member" [13].

The connection mechanism between the FRP material and the structure has also been researched at length. Studies have been conducted on mechanically fastened anchorage systems, which include "steel power actuated fastening "pins" (PAFs), steel anchor bolts or concrete screws, or a combination thereof," and a summary of a decade's worth of research is given in [15].

A study on RC beams strengthened with Powder-actuated fastened (PAF) FRP demonstrated that the strengthening system would continue to provide an increase in flexural strength over the control specimen for several different levels of steel corrosion [16].

Another study investigated concrete beams strengthened with mechanically fastened FRP, using concrete screws as the anchor system [17]. The effects of fastener number, spacing, and pattern were investigated and results showed that this strengthening method increased the flexural strength of the member by 12-39% with little or no loss in ductility.

Shear tests were conducted to determine the interfacial behavior between mechanically fastened (MF) FRP composites and the concrete substrate and an FE model was developed from the results to predict the interfacial behavior [18].

While steel anchors were originally used when prestressed FRP sheets were first used for rehabilitations, recent research has been conducted on the use of nonmetallic anchorage systems including non-anchored U-wraps, mechanically anchored U-wraps, and CFRP sheet-anchored U-wraps [19]. Test results showed that the beams with nonmetallic anchoring systems had comparable load-carrying capacity to the control beam with steel anchorage, while the nonmetallic anchoring systems more efficiently resisted peel-off cracking of the strengthening system.

A 2011 study proposes the use of fiber-reinforced cementitious composite (FRCC) plates glued on top of FRP sheets to act as an anchorage system [20]. Test results showed that this anchorage system can improve the ultimate load and central deflection of strengthened beams compared to beams strengthened without anchors or those strengthened with conventional U-shaped FRP anchors.

"An effective anchorage system allows externally bonded FRP reinforcements to continue carrying load, even after debonding occurs" [21]. A study was conducted to compare three different anchorage systems for shear strengthening of RC T-beams. The anchorage systems tested were "the so-called (1) discontinuous mechanical anchorage (DMA) system, (2) sandwich discontinuous mechanical anchorage (SDMA) system, and (3) additional horizontal strips (HS) system" [21]. "Results showed that the SDMA system performed best, followed by the DMA and HS systems" [21]. The SDMA system increased the shear strength of the beams by 59-91% and altered the failure mode from FRP debonding to FRP rupture. The study also found that the shear contribution from internal transverse steel reinforcement varied depending on which anchorage system was used.

Deck strengthening experiments were conducted to compare MF unbonded FRP and EB FRP with and without end anchorage systems [22]. Results showed that EB

FRP with end anchorage provided the greatest increase in strength, EB FRP without end anchorage provided the greatest decrease in midspan deflection, and MF unbonded FRP performed the worst of the three systems.

In 2011, Lees and Winistörfer discuss the applications of nonlaminated FRP strap elements for strengthening tension members of RC, timber and masonry structures [23]. Nonlaminated straps secure the outermost layers of the FRP by winding the material around supports, thus self-anchoring the system, and leaving the inner layers of FRP nonlaminated, as opposed to laminating the entire strip and winding the ends of the strip around the support. Nonlaminated FRP has produced better results than laminated FRP in tension tests.

Another 2014 study proposed using CFRP rope to anchor U-wrap FRP and create a full wrap [24]. CFRP rope is "a bundle of flexible CFRP strands held together using a thin tissue net" [24]. The full wrap is created by drilling holes in the web-flange intersection, inserting the ropes through the holes, and flaring the ends of the rope onto the free ends of the U-wrap scheme. In this particular study, the CFRP rope covered half the depth of the L-strips used to make the U-wraps. Results showed that the shear resistance of the beam was further increased when CFRP ropes were used to anchor the L-strips compared to beams strengthened with CFRP sheets and CFRP L-strips without CFRP rope. Additionally, this anchorage technique eliminates CFRP debonding and achieves rupture of the steel stirrups.

EB and MF FRP systems have both been used to strengthen concrete beams, but research is being conducted to combine methods to provide a stronger, hybrid bond. One study strengthened RC beams with externally bonded FRP composites and bolted the ends of the composites to the concrete to prevent delamination, and results showed that the hybrid bonding system provided more reliable strengthening than the adhesive bond alone [25]. One experiment used nylon anchors inserted in the concrete prior to installing the fasteners to provide better grasp and resulted in higher load capacity and post-cracking stiffness than the MF-FRP counterpart specimens [26]. This method requires the FRP strips to extend the entire span. Another study of hybrid bonding experimented with the spacing, number, orientation, and composition (carbon versus glass fibers) of spike anchors used in conjunction with U-shaped FRP jackets on RC T-beams [27]. Results showed that "anchors placed inside the slab are many times more effective than those placed horizontally inside the web, and anchors of similar geometrical characteristics (e.g., embedment length) display similar effectiveness despite the difference in fiber type" [27].

In 2014, NSM CFRP was studied in a three-dimensional FE model to "examine the response of the strengthened girder in the vicinity of the anchorage where the NSM CFRP is terminated" [28]. The mode of failure is concrete breakout rather than bolt failure in shear for the end of NSM CFRP strips. It was found that NSM CFRP causes a complex strain distribution near the bottom flange, with some regional rotation of the concrete layer. "An influential zone across the girder web is noticed within which the applied energy is dissipated substantially, in conjunction with the existence of a local tension field" [28].

2.4.2 Near surface mounting composite strengthening systems

Near surface mounting (NSM) involves cutting a groove in the concrete surface in which the repair material will be placed and epoxied. In the case of FRP strips, NSM can decrease or eliminate debonding caused by exposure. One study of NSM FRP strips demonstrated that "Force transfer between the CFRP, epoxy grout, and surrounding concrete was able to develop the full tensile strength of the CFRP strips"

[29]. The NSM technique successfully increased the concrete beam's yield and ultimate strengths, and decreased the energy and deflection ductilities of the beams.

The tensile properties of FRP rod and the mechanics of load transfer between NSM FRP rods and concrete were investigated in reference [30] through tensile and bond tests and full-scale shear strength tests.

A large increase in moment capacity gained by the relatively small amount of material of NSM FRP rods can improve a structure's live load capacity, and is "quite effective for shear deficient elements" [31]. However, this same study warns that NSM cannot be used for seismic upgrading.

According to reference [32], the NSM technique is a better option in hot or humid weather than external bonding. The NSM technique can also be used in lieu of replacing reinforcement on highway bridges with heavy traffic. Small-scale beams reinforced with NSM CFRP rods were tested and results were presented "in terms of load--mid-span deflections as well as in terms of load--first crack width" [32].

Reference [9] gives an overview of experimental tests run "to verify any proposed design approach and to provide information on the practical issues that could be incorporated into the design guidelines" in the United Kingdom, for strengthening bridges using Near Surface Mounted (NSM) reinforcement.

Prestressing the CFRP laminate before bonding it to the concrete allows for a more efficient use of the composite material's strength. Prestressing plates or sheets have been used in practice while studies [33] and [34] propose prestressing NSM CFRP rods. The experimental study conducted in reference [33] showed that similar load carrying capacity was obtained using prestressed NSM CFRP rods when compared to prestressed external steel and CFRP tendons.

Prestressing NSM CFRP rods as opposed to EB CFRP is proposed in [35]. This method more efficiently transfers the shear and normal stresses between the CFRP and the concrete compared to EB CFRP. Test results show that the beams strengthened with prestressed rods experienced a higher first-crack load and a higher steel-yielding load as compared to the non-prestressed strengthened beams. "The ultimate load at failure was also higher, as compared to non-prestressed beams, but in relation not as large as for the cracking and yielding" [35]. The midspan deflection was smaller for the prestressed beams. "All strengthened beams failed due to fiber rupture of the FRP" [35]. Another study produced similar results, reporting, "Beams strengthened by CFRP rod failed due to fiber rupture of the FRP in the groove, but beams strengthened by CFRP plate failed due to concrete cover separation" [36].

A self-anchoring NSM bar was developed in one study, to delay delamination and allow the repair to contribute strength after partial delamination [37]. The bar was designed with a series of monolithic spikes that were embedded deep in the concrete in holes which were drilled into the NSM groove. "The anchors delayed delamination and enabled the NSM bar to experience at least a 77% higher strain at failure than the companion bar without anchors" [37].

The methods of external bonding and near surface mounting FRPs for flexural strengthening have been researched together to determine the advantages and strengths of each method. In the experiments presented in [38], beams strengthened with each method are tested in parallel, using externally bonded U-wraps and NSM CFRP laminates inserted in vertical or 45 degree diagonal pre-cut slits. This study also investigates the "influences of the equivalent reinforcement ratio (steel and laminates) and spacing of the laminates on the efficiency of the NSM technique."

El-Maaddawy and Chekfeh used externally bonded CFRP sheets and NSM GFRP bars to repair concrete T-beams with corroded steel stirrups [39]. The loss of shear strength in the beams was proportional to the loss of cross-sectional area of the steel stirrups. Both strengthening methods were able to restore the shear capacity of the beam. Higher levels of corrosion required greater amounts of strengthening material to restore capacity.

The Kansas and Missouri DOTs conducted a joint investigation of FRP shear strengthening of prestressed concrete bridge tee-girders using manually applied CFRP laminates and NSM CFRP bars [40]. Each girder strengthened in shear was also strengthened in flexure with CFRP laminates. Unfortunately, each strengthened girder failed in debonding of the flexural FRP laminate before other failure modes could be achieved.

Examination of the spacing and end anchorage of NSM rods, the strengthening pattern, and the effect of the presence of internal shear reinforcement was conducted in a study of NSM FRP rods [41]. Results showed that NSM FRP rods could increase the shear capacity of concrete beams significantly, even when shear stirrups were present. The results verified an interaction between the internal reinforcement and the NSM rods, but the increase in capacity gained from the NSM rods was still significant. The failure mode of the beams was debonding of the FRP rods due to splitting of the epoxy cover. It was suggested that this issue can be prevented "by providing longer bond length with either anchoring the NSM rods in the beam flange or using 45-degree rods at a sufficiently close spacing" [41].

New configurations of FRP composites are continuously being researched in order to optimize the strengthening effect of the material. One study paired a GFRP sheet and NSM steel bars and found that the combination provides strength comparable to five layers of CFRP [42]. This material combination was advantageous because the GFRP protected the steel bars from corrosion and the steel bars provided redundancy against environmental degradation or vandalism of the GFRP. When the paired materials both extended the length of the beam, failure occurred at a load 50% higher than the failure load of the layered CFRP. However, when the NSM steel bars covered only 30% of the shear span, the paired material failed at a similar load to the layered CFRP due to NSM delamination from lack of sufficient development of the NSM bars.

NSM GFRP bars were used to strengthen timber beams in an experimental study and results showed that this strengthening technique changed the failure mode from brittle tension to compression failure and increased flexural strength by 18 to 46% [43]. It was also found that NSM GFRP bars overcome the effects of local defects and increase the bending strength of the member. The paper also reports that this method was implemented on a timber bridge near Winnipeg, Manitoba, Canada.

Various NSM FRP reinforcement systems were studied to strengthen concrete bridge slab overhangs and experimental results showed that this strengthening technique successfully increased both yield and ultimate strength of the pre-damaged slab overhangs [44]. Results also showed that all surface treatments tested on the rods, shown in Figure 1, were more effective than the smooth condition, and “the square-shaped reinforcement displayed better performance than the round shape” [44].

A comparative study of flexural strengthening methods was conducted in 2005, led by the University of South Carolina (SCDOT, FHWA) [45]. The three methods of External Bonding (EB), Near Surface Mounting (NSM), and Powder Actuated Fastening (PAF) were compared. The study tested ten small-scale beams and eight full scale girders. Six small-scale beams were subjected to cyclic loading while the other four small-scale beams, one of which was a control, were tested monotonically to

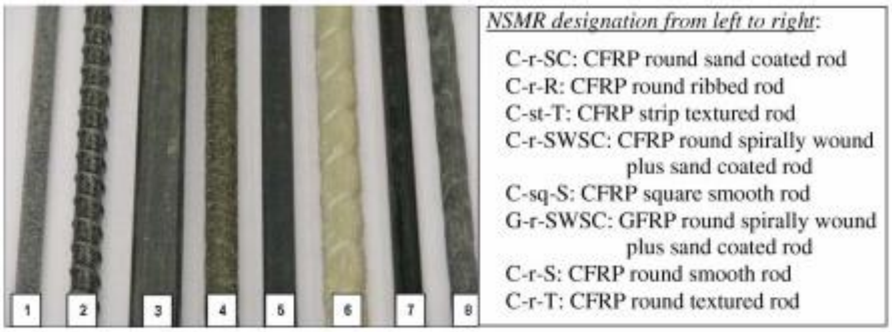


Figure 1. Illustration of various FRP NSM reinforcements. *Figure 1.* Illustration of various FRP NSM reinforcements. Reprinted from "Assessing the strengthening effect of various near-surface-mounted FRP reinforcements on concrete bridge slab overhangs" by D. Lee & L. Cheng, 2011, *Journal of Composites for Construction, 15*(4), p.616. Copyright [2011] by ASCE. Reprinted with permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.

failure. Results showed that the concrete beams tested to failure all failed in concrete crushing except for the beam with EB FRP, which failed in delamination of the FRP at midspan. The fatigue tests showed that EB FRP was also outperformed by the other two methods under cyclic loading. Analytical models were created based on the experimental results of the full-scale girder fatigue and strength tests. The analytical models were designed to predict debonding failure, to understand the influential parameters and discover how to mitigate debonding. Results showed "Midspan debonding failure can be predicted using the intermediate crack induced debonding models provided they account for the ratio of FRP plate to substrate width and loading and specimen geometry" [45]. An FE model was also created. The tests also showed that "the state of stress at an interface crack tip in a reinforced beam under flexural testing is dominated by shear stresses" as opposed to peeling stresses. This means that for the modified double cantilever beam (MDCB) test method, the test set up would need to be modified to allow the shear stresses to dominate.

2.4.3 Post-tensioning composite systems

Analytical modeling has shown that strengthening RC bridges with CFRP laminates leads to a significant increase in strength at the ultimate limit state, while the increase in strength is relatively small at the service limit state [46]. One way to enhance the benefit from CFRP retrofitting on the service limit state is to prestress the composite, which is also known as post-tensioning. The following are three examples of CFRP laminate post-tensioning IBRC applications, and four research studies that focused on improving the anchorage systems for post-tensioned CFRP.

The states had mixed results when implementing FRP post-tensioning bars in IBRC projects. When implemented on a steel girder bridge in Iowa, the P-T bars successfully reduced the dead load and live load moments acting on the member, by 3% and 5%, respectively, which increased the bridge's live load capacity. The P-T bars did not change the stiffness of the bridge and an average loss of 2.6 kips of P-T force (per location) over two years of service was reported [3]. It was recommended that larger or stronger rods be used for projects needing greater increases in capacity.

Ohio also used IBRC projects to experiment with P-T FRP bars, implemented on the underside of deteriorated sidewalk beams of a 6 span precast-prestressed concrete box beam bridge [47]. The strips were attached to the beams with stainless steel anchors mechanically fastened to the beams. The bridge's tensile reinforcement had suffered extensive deterioration. The reference provides design calculations that show the original capacity of the beam could be restored with the post-tensioned CFRP strips. Construction issues that were identified and resolved are also presented in the paper [47]. However, data from load tests of the bridge before and after strengthening showed that the actual increase in strength gained from the FRP bars was insignificant and considerably less than the anticipated increase calculated from analysis. Ohio also used P-T bars on a 4 span steel girder bridge with similar disappointing results, which will be further discussed in Section 3.3.1.4. Suggestions given to improve the results were to use more rods with higher tensioning to better distribute the force.

Numerical and experimental investigations were conducted on a conical casting anchorage system for external prestressing CFRP tendons and results showed that the anchorage system allowed for high exploitation of the mechanical fiber properties which led to high efficiency of the strengthening system [48]. Tests were conducted for 7, 19 and 37 CFRP-wire strands. The first application of external prestressed CFRP tendons in Austria was a strengthening project at the Tauern- motorway bridge in Golling.

One study conducted experiments on RC beams and PC beams to determine the effects of end anchorage and prestressing on FRP retrofits [49]. The results showed that the increase of ultimate capacity depends on many factors, and mechanical end anchorages "delay end and/or intermediate delamination" [49]. The trilinear analytical model developed in this study produced results that correlated well with the experimental results.

Laboratory tested were conducted on sound RC beams and deteriorated RC beams with yielded internal steel reinforcement, after strengthening them with CFRP plates which were prestressed to 0, 25, or 50% of the tensile strength of the plate [50]. Intermediate anchoring devices were installed along the shear span of some of the strengthened beams, providing additional anchorage for the prestressed CFRP plate to delay debonding. Results showed that prestressing the plate and using additional anchorage successfully increased the load capacity of the strengthened beams, independent of the beam's deterioration [50].

A new method of anchoring and applying prestressing force for post-tensioning concrete bridge superstructures, called the lateral post-tension (LPT) method is detailed in reference [51]. The tendon is initially placed straight while the bottom of the girder is cast to match the desired final prestressing profile. The ends of the tendon are embedded in the end blocks to form a dead-end anchorage system, and then the tendons are vertically deflected to the prescribed profile and locked in place. The benefits of simple anchorage and easy stressing method lends this method as an alternative to post-tensioning and allows for easy access for routine inspection, final adjustments, bridge rehabilitation and retrofit construction.

2.4.4 Fiber reinforced cementitious matrix as a strengthening system

"The FRCM is a composite material consisting of one or more layers of cement-based matrix reinforced with dry-fiber fabric" [10]. The research presented in this section investigated varying number of layers, types of fiber, bases for the matrix, and locations of the material on the structure. The effects of field conditions such as fire and creep on the FRCM bond durability were also investigated. Finally, some successful field applications of FRCM strengthening are reported.

Experimental tests were conducted on beams strengthened with FRCM containing 1 layer of fabric and 4 layers of fabric. Results showed that the FRCM improved flexural strength of RC beams but decreased 'pseudoductility.' Beams strengthened with more layers of fabric had a greater increase in flexural strength, and beams with lower-strength concrete had a greater relative increase in strength. "The test results identified two failure modes, namely, fabric slippage within the matrix, and FRCM delamination from the substrate. The failure modes are dependent on the amount of FRCM reinforcement" [10]. Strain compatibility is not satisfied in the retrofit due to the fabric slippage or FRCM debonding. Experimental studies were carried out by the Missouri University of Science and Technology to “isolate the shear debonding phenomenon using single lap shear tests” [11].

Azam and Soudki tested seven shear critical RC beams strengthened with different FRCM layups, altering the material between carbon and glass FRCM and varying the strengthening scheme from side bonded to u-wrapped [52]. Both strengthening schemes exhibited similar results, “suggesting that the excellent bond of the FRCM to concrete may not require u-wrapped applications for anchorage” [52]. Epoxy is not compatible with the concrete, so a cementitious binder provides a better bond [53]. Carbon grid sheets are still the reinforcing material, so the strengthening effect of FRCM is comparable to FRP laminates and is effective in reducing strain in the steel stirrups and reducing surface cracks compared to non-reinforced concrete beams [53].

Steel Fiber Reinforced Self-Stressing Concrete (SFRSSC) has also been investigated as a strengthening material to increase crack resistance of concrete beams and increase the negative moment capacity of continuous beams [54]. Test results indicate “that the composite layers enhanced the cracking moments 44.9% more than conventional concrete layers, though its height is only 13.9% of the cross section height” [54]. The crack resistance of the continuous beams strengthened with SFRSSC in the negative bending moment regions was also greatly improved.

One study investigated four different inorganic pastes to use as a matrix and bonding adhesive for fiber reinforce inorganic polymers (FRIP) [55]. Results showed that magnesium phosphate cement (MPC)-based and magnesium oxychloride cement (MOC)-based inorganic pastes “exhibit similar structural performance as commercially available PMM and are well-suited for the development of FRIP strengthening technology" [55]. The geopolymer (GP) cement was the most brittle of the four pastes studied.

Another study referred to their material as 'textile-reinforced mortar' because the fabric sheets were bonded to the structure with cementitious or polymer-modified cementitious mortar [56]. Tests were conducted on shear deficient beams to study the different mortar types, the number of textile layers and the orientation of the sheets. Test results showed that the TRC successfully strengthened the shear capacity of the beams and the increase correlated with the number of layers used. The system found to provide the highest increase in shear capacity was a higher number of layers with the sheets oriented at 45° and applied with polymer-modified mortar.

A lab experiment was conducted in Switzerland to determine the residual tensile strength of FRCM after exposure to elevated temperatures [57]. These tests involved full scale RC slabs strengthened with a layer of fabric embedded in a layer of shotcrete. Preliminary test results showed that the composite system was effective in increasing the specimen's yield and ultimate loads, that the full contribution of the mesh was reached only after advanced cracking and crack opening, and that the method of failure was slippage of the mesh in the shotcrete. Specimens were heated to 300, 500, 700, and 1000 degrees C and kept at that level for 30 minutes before cooling to ambient temperature. Subsequent tensile tests showed that the residual strength of the mesh dropped significantly after exposure to temperatures higher than 300 degrees. The final test was run on a RC slab strengthened with FRCM exposed to fire for two hours. The specimen held the load for the duration of the test, indicating residual tensile strength of the FRCM. "The internal steel reinforcement did not trespass a critical value of 500 degrees C as proposed by current design recommendations" [57].

The use of Fiber Reinforced Self-Compacting High Performance Concrete (FRSCHPC) as a repair material for bridge planks was investigated in study [58]. The study particularly focused on the creep and shrinkage of the original structure and the repair material and how this affected the bond. Results showed that FRSCHPC was a good candidate for repair material as it produced better results than normal fiber concrete repairs.

RC slab-type elements were strengthened with FRCM in a lab experiment and the results verified that this technique was a viable strengthening option for flexural RC members [59].

Fiber reinforced concrete was applied for the maintenance of the Guan Yin Dang Bridge in China [60]. Field measurements revealed that the application of FRC was effective because the maximum stress calibration coefficient at midspan was less than one, which improved the bearing capacity and deformation capacity of the bridge.

Flaws were contained in the bridge deck paving overlay of the Dongguan Northern Bridge of the Guangzhou-Shenzhen highway in China and research was conducted on the potential retrofit with mesh and steel fiber reinforced concrete (SFRC) [61]. A numerical model was analyzed under unfavorable load positions, taking into account the creep and shrinkage effects of concrete, to determine the interaction between the old and new concrete. The paper also gives a summary of the application of mesh and SFRC to the Dongguan Northern Bridge.

2.4.5 Spray FRP as a strengthening material

The applicability of rehabilitating concrete beams with spray FRP is an area of ongoing research. Banthia and Boyd conducted comparative tests on circular columns repaired with Spray FRP and continuous FRP wraps [62]. Results showed that the spray FRP performed at least as well if not better than the continuous FRP wraps. The tests also revealed that for continuous FRP wraps, a fiber orientation of 0-90° is far more effective than wraps with a ±45° orientation. In a follow up experiment, a comparison was made between SFRP and traditional FRP wraps on full scale bridge girders [12]. Test results showed that both methods increased member stiffness, but the SFRP was more effective. The SFRP method was applied in the field on Safe Bridge on Vancouver Island to repair severe spalling [63]. 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.

Three-point bending tests conducted on concrete beams strengthened with SFRP found that SFRP did not significantly increase the load capacity of the specimen, but did increase the member's deformation capacity [64]. Results also showed that SFRP would be applicable for concrete surface repair and would form a good bond with the substrate.

One study investigated the compressive and flexural performances of small-sized concrete beams strengthened with SFRP and the flexural performance of large-sized concrete beams strengthened with SFRP [65]. U-shaped strips and shear keys were used to improve the bond between the specimen and the SFRP. Test results showed that 30-mm fibers at a 30% fiber volume ratio maximized the strengthening effect of the SFRP without compromising the constructability. The strength gained from SFRP was greater for beams of normal strength concrete than those of high strength concrete. The flexural capacity of the beam increased more when two U-shaped strips were applied at either end of the beam, but deformation was better controlled by a U-shaped strip in the center of the beam.

A comparison of SFRP using glass fibers and traditional GFRP wrap on concrete channel beams showed that the spray GFRP increased the ultimate flexural capacity more than the GFRP wrap, but the wrap was more effective for increasing flexural stiffness [66].

The effectiveness of externally bonded sprayed GFRP used to strengthen RC beams in shear was investigated by Soleimani and Banthia [67]. Different surface preparations involved sandblasting or pneumatic chisel paired with through bolts and nuts were applied to the test specimens. The pairing of through bolts and nuts and surface preparation by pneumatic chisel was found to be most effective in strengthening the bond between the concrete and the sprayed GFRP. Application of the sprayed GFRP on three sides (U-shaped) also provided more shear strength increase than only 2-sided sprayed GFRP. This paper also proposes an equation "to calculate the contribution of Sprayed GFRP in the shear strength of an RC beam" [67].

2.5 Experimental Research of Unique Types of Strengthening

Composite materials are being used to strengthen bridges in many ways besides increasing flexural and shear capacity. Some examples are research conducted to use FRPs to strengthen girders damaged by impact and fatigue, retrofit bridge columns, and strengthen arches and torsional elements.

2.5.1 Impact damaged overpass girders repaired with composites

One area of ongoing research is for strengthening PC girders that have been damaged by vehicle impact [68]. The limits of the methods externally bonding, near surface mounting, and prestressed rods have been investigated in relation to rehabilitation of impact damaged girders [69]. A damage spectrum is outlined with no repair-repair and repair-replace thresholds, giving guidelines on the applicability of each method.

An FEA model was developed to conduct a parametric study of a bridge which had been damaged by truck impact and repaired with externally bonded FRP composites, to determine the load distribution factors for shear, F_v, and moment, F_m [70]. The load distribution factors developed by the model were consistently lower than those obtained through the Canadian Highway Bridge Design Code, which suggests that the code is conservative.

2.5.2 Fatigue damage repair of steel structures

"FRP overlays have been successfully used in the aerospace industry to repair fatigue damage in aluminum plates" [71], which suggests the potential for FRP repair of fatigue damaged steel bridge structures. This is a relatively new area of research and is ongoing. The following subsections present laboratory studies, finite element models developed to investigate this area of research, and field implementations.

2.5.2.1 Laboratory studies of steel fatigue damage repair

A study was conducted to repair steel plates with fatigue cracks with varying thicknesses of CFRP overlays [71]. The different thicknesses provided different axial stiffness ratios which increased fatigue life and decreased applied stress. "Results showed that increasing the axial stiffness ratio from 0 to 0.4 could increase the fatigue life by a factor of 10 for the most extreme conditions, and with an optimal axial stiffness ratio infinite fatigue life may be reached" [71]. An FE model was created which verified the use of axial stiffness as a design parameter and correlated to the experimental results.

CFRP sheets were used to repair damaged steel girders which were composite with a concrete slab, in reference [72]. The steel girders in the study were intentionally damaged to simulate a fatigue crack or severe localized corrosion. Results showed that as more CFRP was applied along the length of the girder, more of the original capacity was recovered, where CFRP covering 97% of the span resulted in a 16% increase over the original strength and a 26% increase over the girder's original stiffness. The study included both standard modulus (SM) and high modulus (HM) CFRP and showed that "SM-CFRP failed by debonding whereas HM-CFRP was ruptured" [72]. The CFRP sheets were bonded to the underside of the tension flange and on some girders also bonded to the top of the tension flange. Results showed that no significant advantage was gained by bonding to both sides of the tension flange.

2.5.2.2 Finite element modeling of steel fatigue damage repair

A Finite Element Method investigation was conducted to compare three different configurations of FRP on a cracked steel plate, to determine which configuration most efficiently extended the crack growth life [73]. Results showed that the effectiveness of the repair depended on the FRP thickness, initial crack length, adhesive thickness, and local debond size.

The use of CFRP overlays to strengthen fatigue-critical welded connections is also being investigated. The CFRP overlay was "bonded over a fatigue-critical weld (AASHTO category E') in a steel test specimen with the goal of reducing the peak stress at the weld" by providing an alternate load path [74]. "FRP materials can have distinct strength advantages over steel when loaded in their optimal orientation, fiber composite materials such as graphite (carbon)-epoxy and Kevlar-epoxy can outperform steel when subjected to uniform tension" [74]. The development of the composite overlay, called a ‘composite doubler,’ is given in study [74]. Results of fatigue testing showed that the CFRP overlays significantly reduce the stress demand on welded connection tested at high stress ranges, which increases the fatigue crack initiation life. The optimal bond composition (epoxy substance and thickness) to extend the fatigue crack initiation life of a welded connection was also identified [75].

2.5.2.3 Implemented steel fatigue damage repair

A pilot program is underway to “allow authorities to exploit the engineering and economic advantages for the refurbishment of steel structures” using composite doubler repairs [76]. A report is given of the application of high modulus FRP composite patches installed on a steel bridge on Interstate 10 and the results. “The factors influencing the durability of composite patches in severe field environments are discussed along with related laminate design, analysis, installation, and nondestructive inspection issues” [76].

In 2014, a new retrofit method was developed for distortion-induced fatigue problems in steel bridges using adhesively-bonded FRP angles [77]. The FRP angles do not require “deck removal or any other severe modification to the steel girder” [77]. The FRP retrofitted specimens have significantly longer fatigue lives than as-welded specimens or specimens repaired by other conventional repair methods. An FE analysis was conducted, utilizing the hot-spot stress method to quantify the effectiveness of the proposed retrofit method. A follow up study conducted fatigue tests on steel specimens modeling the region between a web stiffener and a flange on a bridge girder. The FRP angles increased the fatigue life of the specimens “on the order of several hundred percent” [78]. The study recommends future research on full-scale girder to develop guidelines for design of the FRP angle and adhesive.

2.5.3 Column retrofitting with composites

Several studies have shown that FRP confinement of columns can be used to restore, improve, and in some cases surpass the original design strength of the member [79]. There is a need for fast, durable, and cost efficient repair methods for columns damaged due to impact or deterioration, and Parvin suggests that FRP composites could meet this need [79]. Ibell recommends using a cruciform zone of external confinement on FRP strengthened square or rectangular concrete columns to improve the potential benefits [80].

The UK Highways Agency experimented with FRP wrapping of columns on half-scale model tests and in the field on the A31 Bible Christian Bridge in Cornwall with successful results [81]. This success allowed for FRP wrapping of columns to be implemented on many bridge refurbishment projects in the UK and a standard for FRP strengthening was added to the Design Manual for Roads and Bridges.

New York State DOT (NYSDOT) has several field implementations of FRP repairs, including FRP wrapping of columns. One paper reports on several applications of FRP materials and the in-service performance measured by non-destructive testing [82]. Another paper explains that bridge columns were wrapped with FRP to extend the service life of the concrete columns by sealing the concrete surface and confining future delaminations [83]. An investigation on which method was best for removing deteriorated concrete prior to retrofit was also carried out.

A bridge on Route 233 which carries Washington D.C. traffic to Reagan National Airport was in need of rehabilitation after 40 years of service, as bridge replacement was not a practical option due to heavy traffic [84]. Among other rehabilitations, FRP material was used to wrap severely deteriorated columns to lengthen their service life, and the bridge was able to remain open to traffic throughout the rehabilitation.

Kentucky and Michigan reported using FRP wraps in IBRC projects to protect pier caps and bridge columns from deterioration due to corrosion [3]. Vermont's survey response also reported the use of FRP sheets to protect concrete piers against deicing salts. Carbon and glass FRP wraps were found to be equally effective in slowing the corrosion rate on the IBRC projects. Unbonded wraps reduce stress concentrations in the FRP but are less effective in reducing the corrosion rate than bonded wraps, possibly due to ingress of water along the unbonded FRP-concrete interface.

An experimental study of square RC columns wrapped with CFRP under eccentric loading investigated the influence of the number of CFRP layers, the magnitude of the eccentricity, and the presence of vertical CFRP straps [85]. The columns were tested in compression as columns and in flexure as beams. Results showed "that CFRP wrapping enhanced the load-carrying capacity and ductility of the columns under eccentric loading" [85]. It was also found that "vertical CFRP straps significantly improved the performance of the columns with large eccentricity" [85].

GFRP wrapped rectangular RC hollow bridge piers were studied and results found that the GFRP wrap mainly provided increase in ductility before low strength increments were obtained [86]. Numerical models for hollow rectangular members are proposed by the authors and provide good agreement with the experimental results.

Analytical and parametric evaluations of rectangular columns with spliced reinforcement at the column base strengthened with FRP sheets, under combined flexural-axial loads were conducted by Harajli [87]. Results showed that the spliced reinforcement debonded under the applied load resulting in low flexural capacity unless it was confined with FRP sheets. The confinement "enhanced the bond strength capacity of the spliced reinforcement, increased the steel stress that can be mobilized before bond failure occurs, and consequently improved the flexural strength capacity and ductility of the columns" [87].

A new configuration of FRP column wrapping was proposed in one paper to increase the flexural stiffness as well as axial stiffness of the column, called a sandwich wrapping confining system (SWCS), composed of two faces of FRP separated by an incompressible core [88]. "Unlike conventional FRP jackets, the SWCS can be used to improve the strength, stiffness, and ductility of rectangular columns" [88].

A new method of enhancing bond performance of column wrapping by grooving the surface is proposed by Mostofinejad and Moshiri [89]. Tests of columns strengthened with CFRP applied by EB, NSM, and externally bonded reinforcement on grooves (EBROG) methods were conducted for a comparative study. Results showed that grooving increased the maximum load capacity of the column as well as the maximum compressive stress capacity of the CFRP. About 80% of the carbon fiber tensile strength could be utilized as compressive stresses when the CFRP was applied with grooving in a longitudinal composite, whereas the value was only 13% and 16% when the methods of EB and NSM were used, respectively.

One experiment repaired RC beam-column joints with FRP strips [90]. The specimens were reverse cyclically loaded until they were sufficiently damaged. High-strength non-shrink mortar replaced the damaged, loose concrete in the joints, and the joints were diagonally wrapped in FRP strips, and then reinforced with longitudinal FRP strips which were anchored to the adjacent beams. The retrofit restored the original strength of the specimens and greatly increased the deformation capacity.

2.5.4 Strengthening arch structures with composites

The strengthening of arch structures with FRP is complex due to the simultaneous normal and shear interfacial stresses at the curved FRP-arch bondline [91]. Masonry adds additional complexity to a strengthening project because the material is discontinuous. The applicability of FRP strengthening of masonry arches was investigated and the study showed that FRP strengthening improved the loading capacity and stiffness of the bridge, and also restrained the opening of cracks in the masonry [91]. Shear and peeling debonding of FRP was observed.

> “A new concrete damage model based on the plastic degradation theory has been developed in this study to study the bond behaviour of FRP strengthened concrete structure. This robust model can successfully capture this bond behaviour and simulate the entire debonding process” [91].

This study also included a numerical analysis of the bond behavior and structural response of FRP strengthened masonry arch structures and results, which correlate well to test results, “highlight the influence of the key parameters in the structural response to failure and revealed the mechanisms on how the load is transmitted through this complex multi-component structural system” [91].

Zhou proposes strengthening arch bridges with reinforced concrete yokes [92]. This method was developed by Zhou and was successfully applied to strengthen five bridges. The paper discusses how the yoke prevents crack development in the arch and improves the forcing property of the bridge.

Concrete arches were strengthened with FRP strips in an experimental test and results showed that the FRP successfully increased the failure load of the arch by about 40%, increased the deflection capacity, and changed the cracking pattern [93]. “Edge debonding of the FRP was observed during the test but without causing total failure of the arch" [93]. A finite element model of the arch was created to describe the overall structural response, modeling the arch as a polygon, and produced good results.

The FRP wrap scheme was used to strengthen a historic arch in Colorado, the Castlewood Canyon Bridge. The wrap provided longitudinal reinforcement for flexural enhancement and transverse reinforcement for confinement, shear enhancement, and protection from concrete deterioration and steel corrosion. The bond between the FRP and the substrate was a critical factor in order to increase load carrying capacity and provide good protection against aggressive environmental conditions. Lab tests were run that showed the epoxy breaks down at 446°F and deteriorates under fire, but special treatments can be applied to increase fire endurance. CDOT proposes that degradation of the pull-off strength must be considered in the specifications related to the structural design [3].

2.5.5 Strengthening torsional members of structures with composites

Strengthening beams in torsion with composite materials is an upcoming area of research. One paper reports experimental tests run on the torsional strengthening of concrete spandrel beams with FRP laminates, specifically studying fiber orientation, type of composite, and anchorage system efficiency [94]. The study showed that "FRP laminates could increase the torsional capacity of concrete beams by more than 70%" [94]. RC specimens strengthened by bonding CFRP sheets, were the focus of another study which investigated the behavior and strength of the beams throughout the loading history [95]. Another study investigated RC beams strengthened in torsion with FRP wraps in a variety of configurations [96]. Experimental results showed that fully wrapped beams had increased ultimate torques and enhanced ductility. The paper also reports on a numerical analysis performed by ANSYS which produced predictions which agreed well with experimental results.

2.6 Research of Alternate Applications of Composite Materials

Two of the topics presented in this section, FRP beams as load bearing members and the bridge-in-a-backpack technology, are for new bridge construction rather than strengthening existing bridges. The topic of reinforcing steel structures with composites to prevent buckling applies to bridges and other civil structures as well. Also covered in this section are new materials that are being developed to improve the performance of composite retrofits and prevent brittle failures, and an application method called vacuum assisted resin transfer molding (VARTM) which is being researched to make the method more mainstream in the field of structural rehabilitation.

2.6.1 FRP beams as load bearing members

Most composite materials used in structural applications are strips, plates or fabric wraps for strengthening structural elements. However, research has been conducted to create FRP-reinforced glulam beams as well as entire beams of FRP material and use them as the main load bearing material in a bridge rather than as supplemental strength. However, FRP beams can also be used to increase an existing bridge's capacity by replacing or reinforcing the members. FRP beams offer corrosion resistant material which will lead to much longer service lives, but the initial cost of the beams is much higher than conventional material.

Pultruded GFRP H-shaped beams were used in a laboratory experiment to increase the flexural capacity of a steel girder bridge with a deteriorated RC slab deck [97]. The strengthening effect was investigated by the finite element method under static and fatigue loading.

A demonstration project was carried out on Tom's Creek Bridge in Virginia, where FRP beams were used as the main load bearing material [98]. The project set out to determine long-term in-service performance of the FRP beams and determine bridge design parameters from the data. Five load tests were run at 6-month intervals to determine "a maximum load allowance, *IM*, of 0.90, a transverse wheel distribution factor, *g*, of 0.101, and a maximum deflection of *L/490*" [98]. Two bridge girders were removed after 15 months of service and tested to failure which revealed that the girders had experienced no significant change in stiffness or ultimate capacity compared to preservice values of the beams.

An experiment was conducted to test a bridge constructed with FRP beams as the main load-bearing material with a concrete deck [99]. Results show that the FRP beams meet the serviceability and safety criteria, that "the distribution of the shear and bending moment profiles along the length of the beam progress from the hyperstatic to the isostatic cases" as the load increases, and the prevailing failure mechanism is shear dominated at the support points and joint sections [99].

Several IBRC projects involved FRP beams and are summarized in Table 1.

An IBRC Project in Fairfield, Maine, designed a bridge with FRP reinforced glulam beams connected to an integral reinforced concrete deck. The shear connectors successfully achieved composite action in the bridge. "Inspections performed two and three years later revealed loose and missing nuts at bearing seat and diaphragms and loose lag screws at the FRP termination" but the overall condition of the bridge is still good and the expected lifespan is speculated to equal or exceed that of a typical timber bridge [3].

Table 1. IBRC Projects using FRP Beams

Technology	State	County	Road
Hybrid Composite Beam	IL		High Road Bridge carrying High Road over Long Run Creek
Hybrid Composite Beam	NJ		Route 23 over Peckman's Brook
FRP beams	OH	Defiance, Huron, Miami	Casebeer-Miller Road, TR-114, SR-185
FRP Deck on FRP beams	OH		Eight Mile Bridge
FRP Beams	TX	San Patricio	FM 3284 over Drainage Ditch Gregory Texas
FRP Beams	TX		FM 1684, Drainage Ditch Bridge
FRP Beams	VA		Route 601 over Dickey Creek, Sugar Grove - 2000 IBRC #1

Iowa constructed a bridge of FRP reinforced glue-laminated timber girders with a transverse glue-laminated timber deck for an IBRC project, to determine the long-term performance of FRP strengthened glulam girders [100]. Measurements taken two years after construction did not change noticeably from the test results taken at immediately after construction. The bond between the FRP and timber showed no signs of deterioration and it was reported that the cost of the structure would be the limiting factor for the bridge design.

Ohio reported using FRP beams with an FRP deck in an IBRC project. The deck panels were installed in one day. Difficulties with the straps arose due to temperature changes causing the deck to expand and contract, so it is recommended that the straps or slot holes be eliminated to prevent the buckling. Laminate or plate longitudinal joints are recommended to prevent wearing surface cracking. Ohio used FRP beams on another IBRC project on Casebeer-Miller Rd. The FRP beams were box sections, constructed of FRP plates epoxied to the bottom of three FRP I-beams. Foam-filler was placed between the I-sections and a deck was cast on top, causing the beams to act monolithically rather than as individual sections. Eight of these box sections were used to create a 32 ft. wide deck. This bridge was also built on geosynthetic reinforced soil (GRS) abutments, and demonstrated good compatibility between the two technologies. It was recommended that future inspections give special attention to the bottom plates for sign of distress such as bearing failure near the bolts, separation between modules, or separation from the beams.

Texas built two bridges with FRP beams and conventional concrete decks for the IBRC program. The FRP beams were able to achieve almost full composite action with the concrete decks and they also achieved a high degree of lateral load distribution. Delays were caused to one of the projects due to manufacturing modifications. It is recommended that the beams be fabricated and approved before bridge construction starts, to prevent delays. The beams tested to be stiffer than expected, and it is recommended that very little built-in camber is needed in FRP beams because deflection is minimal under the load of the concrete deck. Small camber will also avoid excessively thickened ends of the bridge deck. Texas reports that the outer FRP beams are the most susceptible to UV degradation, and a gel coat can be applied to protect the beams if it becomes a problem. The resin type used for the bridge beams was a vinyl ester with a fairly high elongation to failure, which was very important to the successful implementation of the beams and similar resin types with similar elongation to failure are recommended for future FRP bridge components.

Funded by the IBRC program, Virginia was the first state to use Strongwell 36-in deep FRP double-web beams (DWB) in a vehicular bridge superstructure. Testing of the bridge revealed that it was stiffer than expected, possibly due to unintended composite action with the glue-laminated timber deck, and the maximum deflection was well within design limits. It was also found that intermediate diaphragms are not necessary for glulam deck-FRP girder bridges, because the AASHTO specification girder distribution factors are so conservative, and it is recommended diaphragms only be used if needed for bracing during construction. Some deterioration or damage was noted on the beams during periodic inspections, but the condition did not appear to worsen over time and the strength and stiffness of the bridge were unaffected. A full report of this IBRC project is given in reference [101].

New Jersey and Illinois reported using Hybrid (Hillman) Composite Beams (HCB) in IBRC projects. "The HCB is comprised of three main sub-components that are a shell, compression reinforcement and tension reinforcement. An FRP box beam shell is pumped full of concrete to provide compression reinforcement and fibers of carbon, glass, or steel are anchored at the ends of the concrete to provide the tensile reinforcement...This technology is being used to reduce long-term costs associated with corrosion" [3]. Illinois had a very positive experience, reporting that the implementation was very successful. New Jersey recommends that a minimum of 7" thick deck with two layers of rebar mat is constructed on top of the girders to avoid any possible differential deflection. It is difficult to verify presence of any voids in the filled concrete. It may also be difficult to make field changes to attach utilities to the beams. Also, the ends of the beams cannot be fabricated at a skew angle, therefore the use of these beams for skewed bridges need to be verified with the designer.

Another new load bearing alternative that the IBRC program experimented with was advanced engineered lumber (AEL) beams. These beams are not made with FRPs, but rather with glue-laminated wood. AEL beams were used on an IBRC project in Maine [3]. The mixed hardwood glue-laminated ties were installed on one span of a railroad bridge, and then visually inspected two years later. Half the ties developed cracks that paralleled the edge joint of the multiple width boards, which coincided with J-bolt screw locations. Large delaminations, both in length and depth were observed on the overhanging portions of the ties. Due to the cracks and delaminations, the ties were removed from service. Unfortunately, AEL beams are not recommended for future use.

2.6.2 Bridge-in-a-backpack: concrete-filled FRP tube arch bridge construction

As one of their IBRC projects, Maine experimented with a new accelerated bridge construction (ABC) method which uses concrete-filled FRP tubes [3]. The FRP tubes are lightweight and do not require heavy machinery to set on site, thus, this construction method has been nicknamed 'Bridge-in-a-backpack.' The FRP tubes are hollow cylinders of woven carbon fabric that is inflated with a balloon and curved around a mold before it is infused with epoxy resin, which will then hold the arch shape. The tubes are transported to the site and installed parallel to each other, as shown in Figure 2.

Figure 2. FRP Arches being lowered into place. *Photo 6.* FRP Arches being lowered into place. Reprinted from *Project case studies for IBRC and IBRD Programs*, D. Paterson et al., 2012, FHWA report, p.860. Unpublished internal document of FHWA.

Once the tubes are placed they are filled with concrete. The FRP arch structure transfers vertical loads on the bridge to internal axial loads in the arch and the concrete in the tubes is ideal for carrying the compression loads. The FRP tubes do not require steel reinforcement because the FRP material is stronger than steel. The FRP tubes also protect the concrete from water and elements, therefore extending the service life of the concrete. Sheet metal is attached to the top of the tubes to create a solid surface for the backfill, shown in Figure 3. Backfill is used to create a level surface with the roadway and then a deck is placed on the bridge. This technology drastically decreases construction time, where multiple projects have been completed in less than two weeks. Figure 4 shows the Neal Bridge, completed in 2008, which was Maine's IBRC project, and the first bridge built in the United States to use this technology.

Figure 3. Sheet metal installed on FRP tubes. *Photo 7.* Final arch placement with corrosion resistant decking being installed. Reprinted from *Project case studies for IBRC and IBRD Programs*, D. Paterson et al., 2012, FHWA report, p.861. Unpublished internal document of FHWA.

Figure 4. Completed Neal Bridge. *Photo 1.* Completed Neal Bridge. Reprinted from *Project case studies for IBRC and IBRD Programs*, D. Paterson et al., 2012, FHWA report, p.858. Unpublished internal document of FHWA.

The project was a great success, reporting no negative results, and the technology was used on a state-wide program to build short span bridges quickly and inexpensively.

2.6.3 Steel buckling reinforcement with composites

Much of the applications of FRP strengthening are for concrete structures, especially for shear strengthening. However, an effort is being made to increase the appeal for FRP shear strengthening of steel structures.

Layers of CFRP strips were bonded to the webs of steel I-beams in study [102] to determine the effectiveness of bonding to one side or both sides of the web, and to determine how much area should be bonded. Results showed that steel beams strengthened with CFRP strips had an increase in load bearing capacity of up to 51% and their deformations also decreased. Test results also showed that when bonding CFRP to both sides of the web less material can be used to achieve the same strengthening effect. The governing failure modes for the CFRP strips were longitudinal delamination near the point load and debonding of the strips, where debonding was more critical in the compressive region of the web than the tensile region.

Small scale experimental tests were run to investigate a system of steel bars sandwiched between thin mortar or PVC blocks wrapped in CFRP sheets, to determine if the buckling behavior was improved by the CFRP wrap [103]. Results showed that the inelastic axial deformation capacity prior to buckling and the load carrying capacity after buckling of the steel bars were both improved by the CFRP wrap.

Strengthening-By-Stiffening (SBS), a method which “was proven to be a viable technique for inhibiting local buckling in shear-controlled steel beams” has also been investigated [104]. SBS relies on the out-of-plane stiffness of pultruded composite sections as opposed to the in-plane strength of thin composites” [104]. This study explains that relying on the in-plane strength of thin FRPs, as when applied to concrete structures, would require a relatively large amount of composite to strengthen steel in shear because the strength of steel is so much higher than that of concrete. This study investigated the effect of the slenderness of the strengthened plate on the efficiency of the strengthening and found that girders with thinner webs (1/8”) gain a higher percent increase in shear strength (44.7%) than those with thicker webs (5/16”, 6.7% increase). Research is ongoing to determine the applicability of SBS for full scale steel girders.

2.6.4 Efforts to improve composite material properties and behavior

The problem of brittle failure of FRP retrofits is an area of ongoing research. One method used to create a more ductile composite is to use a combination of carbon and glass fibers. An experiment conducted by the American Concrete Institute designed a uniaxial fabric that would yield simultaneously with the steel reinforcement [105]. Results from beams strengthened with the new fabric demonstrated higher yield loads and higher ductility than beams strengthened with exclusive carbon fiber systems. Another experiment by ACI tested a triaxially braided ductile FRP fabric for flexural strengthening of cantilever and continuous RC beams [106]. The braided fabric allowed greater ductility of continuous beams because it allowed for plastic hinges to form which led to the redistribution of moment in the beam. "Redistribution of the moment enabled the full use of the strength of the beam at cross sections of maximum positive and negative bending moments" [106]. These two new fabrics were hybrid, pseudo-ductile FRP systems, each containing both carbon and glass fibers [107]. Experimental results show that both systems may optimize FRP properties without the drawback of brittle fracture.

In 2009, an experiment was conducted using a ductile anchor system with FRP sheets [108]. The steel anchor system made up of steel links is designed to yield before the FRP sheet ruptures or debonds, leading to a ductile failure rather than a brittle failure. Results demonstrated that the hybrid system was able to increase ductility of retrofitted RC beams while also increasing the flexural capacity.

Polyethylene terephthalate (PET) FRPs are a new type of FRP material characterized by a much larger rupture strain (LRS) than conventional FRPs (carbon, glass, aramid). Research is ongoing to use these materials for bridge rehabilitation. One study demonstrated that using LRS FRPs to fully wrap concrete members shifted the shear failure mode from brittle to ductile and that the ultimate state of the member is no longer controlled by FRP fracture [109].

Prestressing FRP composites allows for more strength to be gained from the composite material in a retrofit. Research is ongoing to improve the ductility of the prestressed FRP in order to gain a better bond with the concrete substrate. Dry fiber sheets are more ductile than precured FRP sheets but have a much lower tensile capacity. One study experimented with partially impregnated carbon-basalt hybrid fiber sheets (CBHFS) to improve the tensile capacity of dry fiber sheets [110]. Results showed that comparable increase in flexural performance could be gained with prestressed EB CBHFS compared to traditional prestressed EB FRP.

Experimental tests have been conducted to determine the performance of RC beams strengthened externally with parafil rope [111]. Parafil rope is made up of parallel aramid fibers encased in a plastic sheath, and so is better for post-tensioning than steel because it resists corrosion as an FRP composite. This study was conducted to provide lab data needed to form a foundation for field implementation.

2.6.5 Vacuum assisted resin transfer molding

FRP composites are most commonly applied by hand in the field, which results in a product that does not have even epoxy distribution and produces variable products from one project to another due to human error. Vacuum-assisted resin transfer molding (VARTM) allows for much better quality control, reducing the occurrence of voids, and evenly distributing the epoxy throughout the fibers. VARTM is widely used in other industries such as automotive and aerospace because it produces a superior final product compared to wet hand lay-up, but VARTM has been limited in the field of civil engineering due to the more complex setup, and the machinery required, which both increase the time and cost of the application. Research is ongoing to make VARTM a more mainstream field technique.

Luis Ramos conducted his doctoral dissertation on the applicability of the VARTM method to strengthening concrete beams. One major concern he addressed was the additional installation time of the FRP retrofit when VARTM is used. Grooving the surface of the concrete beam prior to using VARTM was investigated and proved to reduce the wet-out time significantly, to only 22% of the wet-out time with no grooves [112]. A composite's wet-out time is the time needed for epoxy to saturate the entire composite. He also tested the beams to determine if the grooves were detrimental to the ultimate strength provided by the repair and found that they have no significant effect on the increase in ultimate capacity of the beam [113]. He found that "Beams in these tests wrapped with VARTM FRP have 19% more ultimate flexural capacity and 10% more ultimate shear capacity than beams in these tests using hand layup FRP" [113]. Finally he examined the durability of VARTM FRP and found that VARTM FRP loses more strength over time compared to the hand lay-up FRP. This is most likely due to the absence of excess resin to act as a protective layer against the environment [113]. In 2004, the VARTM method was used as a demonstration project on a bridge on I-565 in Huntsville, Alabama [114].

One study suggests wet lay-up of chopped glass fiber mat using VARTM [115]. The authors propose that this method produces more ductile and resilient FRP than continuous fiber composites which fail in a brittle manner, and they also claim that this method is less messy than the spray method. Experimental results showed that beams strengthened with this method increased the flexural capacity and stiffness of the beams and led to more ductile failure than beams strengthened with CFRP plates.

2.7 Miscellaneous Research Topics of Interest

The development of new bridge strengthening techniques also creates other areas of research related to strengthening. Measuring the strength of a bridge is a valuable practice for bridge owners, both for preventative maintenance and to verify the effectiveness of strengthening systems. Fatigue performance of structures strengthened with composite repairs is a large concern in the research world, along with the effect of different loads on composite-retrofitted structures. The efficiency of composite repairs on strange bridge geometries is also discussed in this section. Finally, strengthening the bridge by modifying its overall structure rather than providing supplemental material is addressed.

2.7.1 Measuring bridge strength

Load testing is a method to measure the capacity of a bridge under worst case scenario design loads. The bridge's girders and/or deck are instrumented with strain gauges that will send data to a computer, and a loaded design truck is positioned on the bridge to induce a force on the bridge. Load testing is a more accurate way to obtain your bridge's capacity than using computational models, because it uses data from the actual structure in field conditions. After testing a load posted bridge, it could possibly be found that the bridge does not actually need to be strengthened, because it was designed using a more conservative code. Load testing is also a way to verify new innovative strengthening techniques worked to strengthen a structure, immediately after the retrofit, or after several years of service.

Four different CFRP systems, including two different widths of bonded CFRP plate, bonded CFRP plate with end anchorage, and bonded CFRP fabric, were all installed on a three-span reinforced concrete slab bridge to increase its capacity [116]. Load testing was conducted before retrofitting, shortly after retrofitting, and after one year of service to measure the bridge's capacity. The CFRP plates and fabric successfully increased the capacity of the bridge and increased the load rating factor by 22%. The retrofits were still performing well after one year of service, showing no adverse reaction to environmental exposure. Engineers were able to remove the load posting on the bridge due to the increased capacity and satisfactory performance. Long term testing needs to be conducted to determine the differences between the strengthening systems.

The strength of a bridge can change over time, so a system that monitors these changes can expedite preventative maintenance and also verify that strengthening retrofits are still effective. Structural Health Monitoring (SHM) systems have been designed, experimented with, and implemented in the field, to allow bridge owners to monitor their bridges [117]. Several states used IBRC funds to install SHM systems on their bridges, which are listed in Table 2.

Table 2. IBRC Projects using Structural Health Monitoring Systems

State	**Bridge**
FL	Hillsboro Canal Bridge
HI	Kahoma Stream Bridge
HI	Kealakaha Stream Bridge
IL	I-39 over Kishwaukee River
LA	I-10 Twin Span Bridge over Lake Pontchartrain
MI	City of Southfield Bridges
MI	Parkview over US 131
NM	I-40 Tucamari/ E. Interchange
UT	F-54, F-156, and C846
VT	Bridge 213 carrying VT Rte 100 over Ryder Brook

SHM systems have an advantage over load testing because the system is installed on the bridge and left there to gather a continuous stream of data rather than being removed after collecting numbers for a single load test. For this reason, SHM systems are more expensive than a load test.

2.7.2 Fatigue performance of structures strengthened with composites

Since composites are relatively new in the structural industry, long-term behavior is a concern that has generated much research, especially the fatigue performance of structures strengthened with composite materials.

The effect of NSM CFRP rods on fatigue life were investigated in [118]. The RC beams strengthened with NSM CFRP rods had a fatigue life 24% higher than the control beams. The NSM CFRP rods also increased the yield and ultimate loads of the strengthened beams by 26 and 50% respectively, compared to the control beams. An analytical model was developed to estimate the fatigue life of specimens at various cyclic load ranges and good correlation of the experimental results and analytical prediction was obtained [118].

The fatigue performance of concrete structures strengthened in shear with FRP materials is of particular concern to the research world. Several references were found studying the fatigue behavior of beams rehabilitated with EB FRP [119, 120]. Results of studies [119]. show that FRP retrofits successfully extend the fatigue life of RC T-beams strengthened to repair or upgrade their capacity. This study also revealed that steel stirrups enhance fatigue performance, but decrease the gain contributed by the FRP, which verifies that there is an interaction between transverse-steel reinforcement and EB-FRP. The experimental results of [120]. show that RC beams strengthened with EB FRP could withstand 2 million cycles of cyclic loading without failure. The study also suggests that "limiting the interfacial stress in CFRP strips to less than 1.5 MPa or 25% of its ultimate interfacial strength would increase fatigue life by avoiding debonding of CFRP strips" [120].

The fatigue behavior of structures strengthened in flexure with FRP has also been investigated. One such experiment studied RC beams strengthened with CFRP under aggressive environments including freeze-thaw, extreme temperature, ultraviolet exposure, and relative humidity cycles [121]. The study showed that the “beams survived 2 million fatigue cycles without showing significant bond degradation between composite and substrate,” but the flexural stiffness of the beams degraded significantly [121]. The flexural stiffness of the beams was also affected by defects in the FRP, but growth in the defect size due to the fatigue loading was limited. Another study looked at the fatigue performance of corroded RC beams subjected to further corrosion after repair [122]. The corroded beams were wrapped in GFRP U-wraps and also strengthened with EB CFRP to increase the flexural strength. The results showed that “Reinforcement steel pitting due to corrosion reduced the fatigue life significantly” [121] and that the GFRP wraps did not significantly affect the fatigue performance, while the CFRP sheets successfully increased the flexural strength, which led to significantly enhanced fatigue performance.

2.7.3 Effect of load on FRP repairs

The effect of limited overload on FRP strengthened structures was investigated with particular focus on establishing the relationship between the amount of FRP and ultimate load [123123]. The influences of limited overload on flexural strength, deflection, crack width and height of bridges were also studied.

The effect of transient traffic loads on the bonding and ultimately the capacity of CFRP retrofits was investigated by Wang, Dai, and Harries [8]. The results indicated “that a 1-Hz sinusoidal transient load varying between 30 and 50% of the ultimate capacity of the unstrengthened beam during the installation and curing of the CFRP sheets does not affect the structural performance of CFRP-strengthened RC beams” [8]. This study verifies that CFRP repairs may be conducted on structures subjected to continuous traffic loads. Ibell confirms that transient traffic load on a strengthened bridge during cure "adversely affects the adhesive but this does not seem to be detrimental" [80].

The effect of high rate loading was also studied [124124]. RC beams were loaded under stroke rates that ranged from 0.0167 mm/s (slow rate of loading) to 36 mm/s (fast rate of loading) which induced strain rates in the CFRP of 2.96 με/s (slow rate) to 6,930 με/s (fast rate). Rapidly loaded beams showed about a 5% increase in capacity, stiffness, and energy absorption. "Ductility and the mode of failure were not directly affected by the change in loading rate. Precycled beams performed similarly to the beams loaded monotonically to failure but showed a 10% increase in service stiffness and a 10% loss in energy absorption" [124]. An FE model was created to predict the moment-curvature response of CFRP strengthened RC beams and includes the effects of strain rate which correlates well with experimental data [124].

2.7.4 Unusual bridge geometries

Research is being conducted to understand the effects of FRP retrofitting on problem areas such as variable cross section beams [125]. Study [125] comments on the many bridges in the UK that have deep main bridge decks and shallow cantilever verges, where the verges need to be strengthened to meet capacity requirements. However, strengthening the verges is not a trivial project, as the effects of cracking and longitudinal shear stresses dramatically reduce the degree of strengthening which can be achieved. Test results show that when little or no cracking occurs in a non-prismatic beam, the FRP may debond locally or globally, resulting in a loss in strength. The study proposed a better approach for analyzing these beams than what is given in the current design guidelines, which are proven to be overly conservative in most cases.

Ibell reports that concavely curved beam soffits reduce the strengthening effect of FRP due to premature debonding, but this can be overcome by a “fan-anchor” system [80]. Ibell also reports “Skew bending is a serious problem because lateral debonding of the FRP occurs parallel to the skew crack” [80].

Finite element modeling is an important step in the design process for both new and rehabilitation construction. It is invaluable to have the ability to predict how a structure will perform subject to specific loading conditions. This can also provide a means of contrasting different rehabilitation schemes to determine which method provides the most benefit before implementation. Carmichael and Barnes developed a finite element model (FEM) for their bridge rehabilitation where a reinforced concrete bridge was strengthened by externally bonding CFRP strips to the soffits of the (varying cross section) girders [126]. Their model showed good correlation between the theoretical and experimental strains in the steel, and demonstrated that the reduction of the strains in the steel could be predicted by linear-elastic, cracked section analysis [126].

2.7.5 Modifying bridge structure

The bridge’s overall structure can be modified to increase the structure’s strength when necessary. Converting continuous multi-span bridges to network arch bridges and converting non-integral abutments to integral abutments are discussed in this section.

2.7.5.1 Converting a continuous multi-span bridge to a network arch bridge

A network arch was constructed on the San Luis Bridge in Chile to upgrade and convert the RC bridge with continuous beams over four spans to a tied arch bridge [127]. The bridge piers were removed after the upgrade, as shown in Figure 5, which eliminated the problem of scouring which the bridge had previously experienced, leaving a stronger, more durable structure. This strengthening technique is aesthetic and economic, as it reduces required maintenance, and is recommended for structures with similar scouring concerns in need of strengthening.

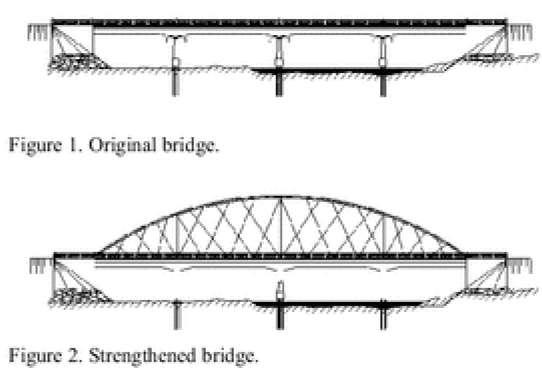


Figure 5. Conversion of continuous multi-span bridge to network arch bridge. *Figure 1.* Original bridge, and *Figure 2.* Strengthened bridge. Adapted from "Bridge strengthening by network arch: Structural performance and design criteria." by M.A. Valenzuela, & J.R. Casas, 2012, *Bridge Maintenance, Safety, Management, Resilience and Sustainability,* p.3919, F. Biondini & D.M. Frangopol (Eds.), 2012, CRC Press. Copyright [2012] by Taylor & Francis Group. Reprinted with permission.

2.7.5.2 Converting non-integral abutments to integral abutments

Joints in a bridge allow for debris and water to infiltrate to the superstructure, requiring maintenance to keep the bridge functional and maintain capacity. Converting jointed decks to continuous decks is one practice that decreases maintenance costs and also increases the capacity of the bridge by converting simple spans to be continuous. An innovative twist on this strengthening method that is gaining popularity is to convert non-integral abutments to semi-integral or integral abutments. Historically, abutments located at the ends of a bridge have been connected to the bridge with joints, allowing the deck to expand and contract freely. In the last two decades, integral abutments have been developed where the bridge deck and the abutment form one structure without any joints between them, as shown in Figure 6.

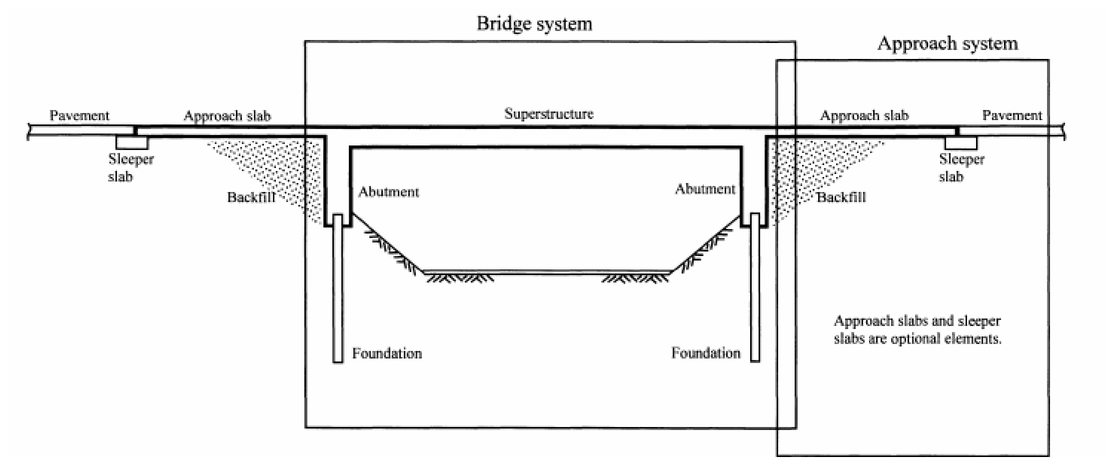


Figure 6. Simplified geometry of an integral abutment bridge. *Figure 1.* Simplified geometry of an integral abutment bridge. Reprinted from *The Behavior of Integral Abutment Bridges*, by S. Arsoy et al., 1999, *FHWA/VTRC 00-CR3*, p.2. Copyright [1999] by Virginia Department of Transportation.

In an integral abutment, force is transferred into the soil behind the abutment instead of dispersing in the movement of a joint, therefore soil conditions are a large factor in the design. The abutment and foundation piles move with the bridge deck as it expands and contracts, subjecting the entire system to cyclic loading, which must be understood for effective design and satisfactory performance [128].

Many new bridges being constructed are now designed with integral abutments, but the conversion of non-integral abutments of existing bridges to integral abutments is also taking place at in increasing rate. In 1999, Ontario reported “Only a few conversions have been made so far but it is expected that this trend will take place at an increased pace in the future" [129]. Kunin and Alampalli published a report, also in 1999, that this method had already been implemented in several states, including Colorado, Tennessee, Illinois, Kansas, Oklahoma, North Dakota, South Dakota, and Wyoming [130]. An FHWA report from 2005 added New Mexico, Missouri, and Virginia to the list [131]. Burke reported that the Ohio DOT had also successfully converted non-integral abutments to achieve integral or semi-integral bridges [132]. Alberta encourages their transportation agencies to convert "existing bridges with conventional abutments into semi-integral bridges in rehabilitation projects where the costs can be justified" [133]. Since Alberta increased the limit on length of new integral designs, approximately 90% of all bridges in Alberta, which are shorter than 100 m are now potential candidates for conversion to semi-integral [133].

Chapter 3

LITERATURE REVIEW: FIELD IMPLEMENTATIONS AND LESSONS LEARNED

This chapter presents a collection of representative field implementations of new bridge strengthening methods and the lessons learned from these projects. Lessons learned were reported in the IBRC reports, the survey responses, and the literature. A list of specifications and guidelines regarding bridge strengthening with composite materials is given at the end of this chapter.

3.1 Innovative Bridge Research and Construction Program Overview

State IBRC projects using innovative technologies for bridge repair are summarized in Table 3. As shown below, a majority (about 85%) of the repair or strengthening projects involved fiber reinforced polymer (FRP) composites as the innovative technology. An overview of the IBRC program projects involving composite materials is given by J. M. Hooks [134]. (Note: most of the FRP deck projects were new bridges being constructed, only about 25% were replacement decks, but lessons learned from constructing new FRP bridges can also be applied to replacing deteriorated concrete decks with lightweight FRP decks.)

Table 3. Summary of IBRC Projects by Category

Technology	# of IBRC Projects	States where Implemented
FRP bonding	26	AL (4), CO, DE (2), GA, HI, IA(2), KY (5), MA, MI, MO, NM, OR, PA, PR, TX, WA, WV
FRP P-T	3	IA, OH (2)
FRP Deck	29	CO, FL, HI, IA(3), IL (2), IN, MD, MO, NC, OH (3), OR (2), PA (5), PR, SC, VA (2), WA, WV (2)
Aluminum Deck	2	KY
Glulam Beams/Deck	6	IA, LA, ME (3), PA
SPS Deck	1	TX
FRC deck	3	IA, MO, VA
Total	**70**	**27**

3.2 Survey Results

A short five question survey created with SurveyMonkey was sent out to over 150 contacts from several committees and teams of the Transportation Research Board (TRB), Federal Highway Administration (FHWA), and the American Association of State Highway and Transportation Officials (AASHTO). The survey questions focused on identifying which new bridge strengthening methods the contacts were aware of and had direct experience with. The questions are listed in Appendix A.2. The groups contacted are listed below:

- TRB Bridge Preservation Committee (AHD37).
- TRB Structures Maintenance Committee (AHD30).
- Friends of AHD30.
- TRB Long-Term Bridge Performance (LTBP) Committee: Expert Task Group for Bridge Durability and Preservation (B0122A).

- FHWA Bridge Evaluation Quality Assurance in Europe: Team Members.
- FHWA Bridge Evaluation Quality Assurance in Europe: Host Country Contacts.
- AASHTO T-9 Bridge Preservation Subcommittee.
- Select contacts from AASHTO Subcommittee on Bridges.

The survey was initially sent out on February 11, 2015. Two reminders were sent out on February 25 and March 4, 2015. Of the 156 individuals contacted, 51 responded to the survey. This gives a response rate of 32.7%. The responses came from 29 U.S. states, highlighted in blue in Figure 7, and three foreign countries: Denmark, Norway, and Canada (Saskatchewan Province).

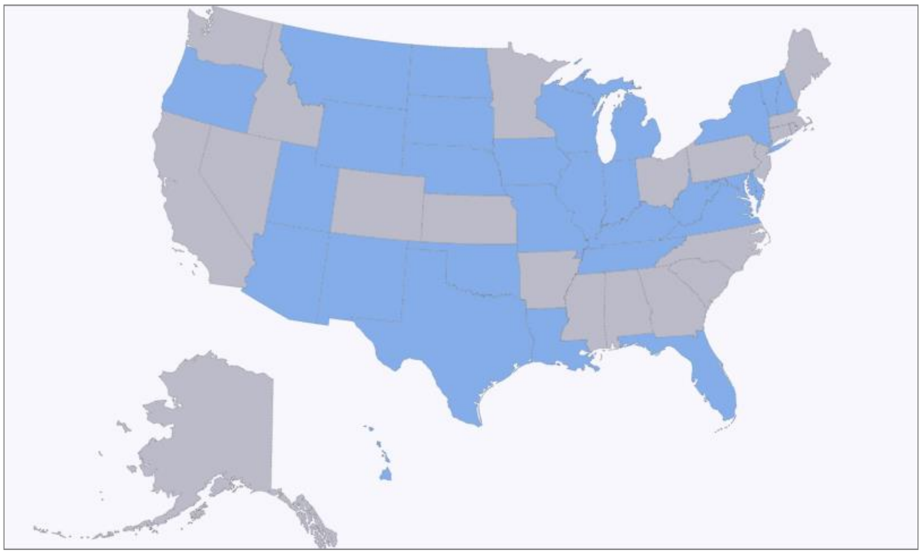


Figure 7. Locations of U.S. Survey Responses.

FRP sheet/plate bonding to increase flexural or shear strength were the most commonly known methods and the ones with the highest reported direct experience, as shown below in Figures 8 and 9. About 90% reported awareness of the use of FRP bonding to increase both flexural and shear strength. Approximately 60% of the respondents reported direct experience using FRP bonding for either flexural and shear strengthening. FRP post-tensioning bars were reported to be as well known as FRP decks by about 60% of the respondents, but, only 14% reported direct experience with FRP post-tensioning bars while 25% reported using FRP decks for strengthening projects. In contrast, only six individuals, or 12%, reported knowing that spray FRP was available as a strengthening method, and only one person (less than 2% of the respondents) reported having worked directly with spray FRP.

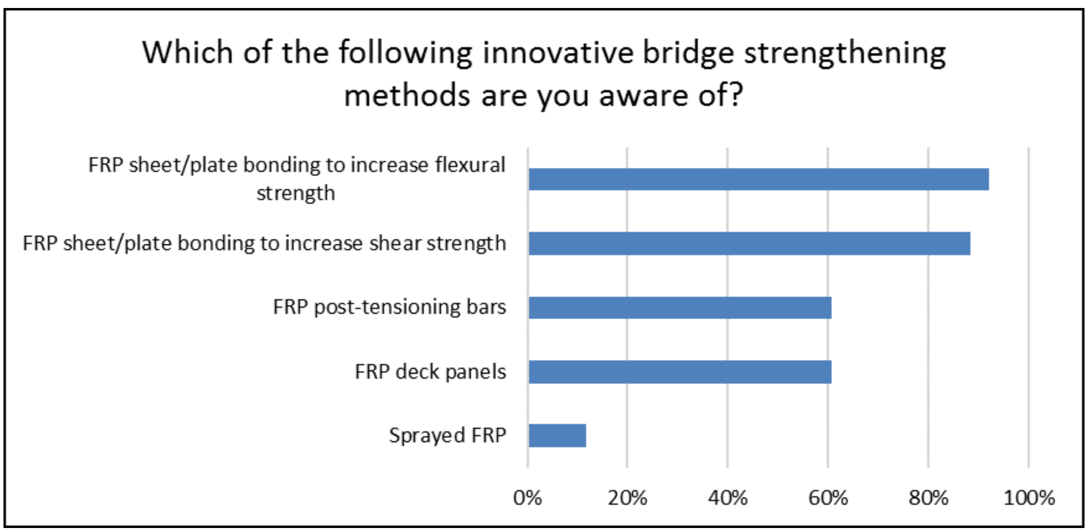


Figure 8. Survey Question 1 Responses

Survey participants reported a few novel technologies that their agencies and organizations have been experimenting with in the last two decades. These new technologies included fiber reinforced cementitious matrix (FRC PBO), strengthening with titanium bars (one project in Oregon), steel reinforced polymer (SRP), and FRP prestressed beams. Survey results indicated that FRPs have also been used for column confinement, to increase impact resistance, and to repair minor flaws (temperature cracks, impact damage, etc.).

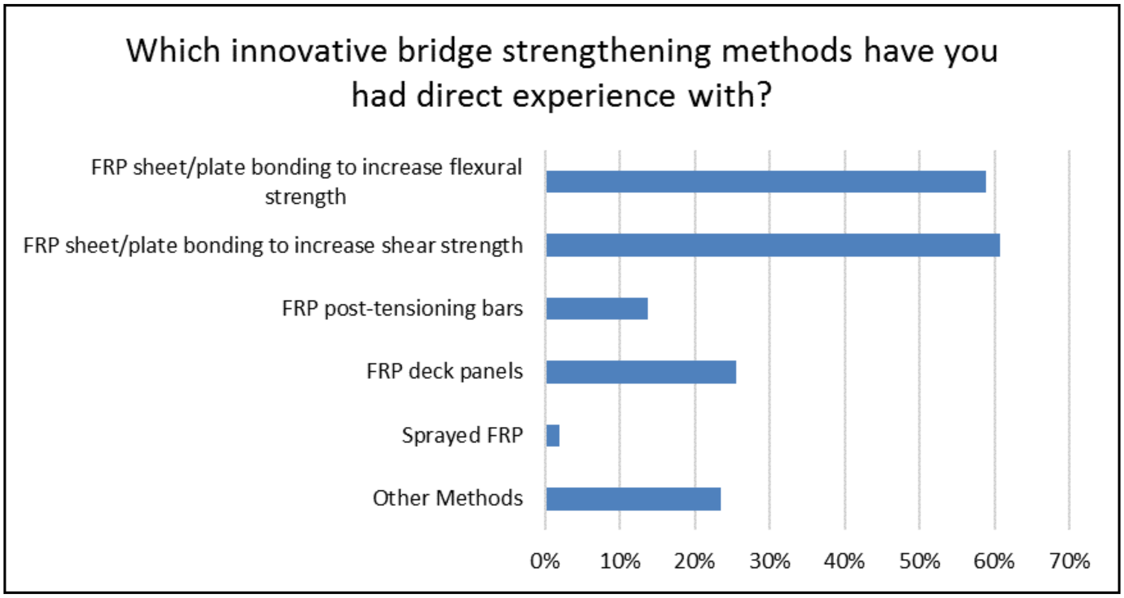


Figure 9. Survey Question 3 Responses

Lessons Learned which were reported in the survey results were often similar to those learned in the IBRC/IBRD projects, which will be covered in Section 3.3. First off, 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. Oregon reported that CFRP and titanium rods are more durable and reliable than FRP sheets and the original anticipated 20 year lifespan of these repairs has increased to 30 or 40 years!

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 was given 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 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 they had difficulty successfully implementing FRP decks, but that FRP wraps work ‘fairly well.’ A representative from the University of Tennessee, Knoxville, reported that FRP materials behave linearly up to failure, providing almost no ductility compared to conventional materials, and “FRP is weak when resisting compression” (survey, February 11, 2015). A New Mexico State University representative reported that the shear strengthening effect of FRPs on bridges with diagonal cracks is still uncertain (survey, February 11, 2015).

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 presented numerous times in the survey results (specifically FRP wraps for shear strengthening of columns). Others commented that manufacturing support is needed to standardize material properties of FRP materials, as now they are proprietary. Also, this standardization would probably 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. Mr. Ayaz H. Malik, former NYSDOT Project Engineer, cautioned that longtime maintenance issues should always be considered when rehabilitating existing bridges and that "structural redundancy, durability, constructability, and ease of inspectability should always be provided as much as possible" (survey, February 11, 2015). He said, "Long time field effects of new materials, like creep effects play an important role in innovative bridge strengthening strategies" (survey, February 11, 2015). Finally, the need for promotion of FRP repair methods was reported as necessary to make them more mainstream.

3.3 Bridge Strengthening by Category

This section is organized by type of bridge strengthening and covers flexural strengthening, shear strengthening, increasing live load capacity through the utilization of lightweight decks, and deck strengthening. The following sub-sections cover general information and instances of field applications taken from the literature, and experiences and lessons learned from IBRC projects.

3.3.1 Flexural Strengthening with Composites

Composites have been used to increase the flexural capacity of concrete beams, concrete slabs, timber beams, and steel beams. 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 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 take dead load. Alternatively, the composite can be post-tensioned prior to applying it to the member, which will allow it to carry a greater portion of the live load and thereby further increase the live load capacity of the structure. In cases where redecking will occur, application of the repair prior to replacing the deck allows the FRP to help carry the new deck dead load.

3.3.1.1 Concrete beams strengthened with composites

An overwhelming majority of flexural strengthening with composites is conducted on concrete structures. An early report of the behavior of RC beams strengthened with CFRP plates, written to provide a foundation for future field implementation, is given in reference [135].

Experimental tests were carried out to determine the 'most effective concrete substrate repair method and FRP strengthening scheme' for T-beam rehabilitation with EB FRP [136]. The two substrate repair methods compared were Crack Filling Only (CFO) where no damaged concrete was removed prior to retrofitting with FRP and cracks were filled with epoxy, and Polymer Modified Concrete (PMC) where "the damaged old concrete was removed to the level of reinforcement and replaced with high-strength polymer concrete containing corrosion inhibitor" [136]. Test results showed that CFO-repaired beams outperformed PMC-repaired beams immediately after repair but after exposure to additional corrosion the PMC-repaired beams provided better durability. After additional corrosion, the CFO-repaired beams experienced severe cracking, mass loss, and reduction in flexural strength attributed to the remaining chloride ions in the damaged concrete. The authors suggest further study of the repair methods with the addition of electrochemical chloride extraction.

Study [136] also compared strengthening schemes anchored with various numbers of U-wraps. Scheme 1 had no U-wraps, scheme 2 had two U-wraps, and scheme 3 had U-wraps distributed along the length of the beam. Test results showed that the additional anchorage did not significantly influence the maximum load capacity, but did increase the member stiffness and the minimum load causing crack initiation. The authors proposed that when long-term effects are considered, more anchorage would most likely provide a "safer long-term repair" [136].

Kansas State University determined that bonding CFRP laminates in a U-wrap to anchor flexural CFRP bonded longitudinally to the soffit of rectangular and T-shaped concrete beams provides the shear resistance and additional anchorage needed to create a stronger bond than bonding to the soffit alone, and allows the CFRP to reach full capacity and rupture without debonding [117].

An investigation was conducted on the combined reinforcement mechanism of CFRP bonding in conjunction with external prestressed steel rods for the strengthening of hollow beam bridges in China [137]. The CFRP bonded to the underside of the beams prevents future cracks from forming while maintaining ductility and the external prestressed rods closed already existing cracks in the bridge. The authors propose that using two strengthening schemes together produces a better result than relying on one alone, as the individual strengths of the methods overcome the counterpart's short-comings.

North Carolina DOT conducted a research project on strengthening of prestressed concrete girders with various CFRP systems [138]. "Results show that the ultimate capacity of prestressed concrete bridge girders can be increased by as much as 73% using CFRP without sacrificing the ductility of the original member. Transverse CFRP U-wrap reinforcements are recommended along the length of the girder to control debonding type failures" [138].

Experimental tests have been conducted to determine the flexural response of EB CFRP strengthened members with internal or external unbonded post-tensioning tendons [139]. These members were tested in parallel with bonded post-tensioned members and RC members. A design model was developed to calculate the flexural capacity of CFRP-strengthened unbonded post-tensioned members, which shows that EB CFRP is a valid strengthening option for these types of members.

CFRP materials were used by the University of South Carolina to strengthen a one-way concrete slab with CFRP strips bonded to the soffit of the slab and a two-way concrete slab by bonding CFRP grids or bonding CFRP strips in both directions to form a grid pattern on the soffit of the slab [140]. This bonding to the tension face of the deck slab can greatly increase its flexural strength.

Prestressed CFRP laminates are also used to strengthen concrete slabs as prestressing allows the retrofit to more fully contribute to improving the serviceability limit state, increasing the cracking moment, and limiting deflections [141]. The efficiency of strengthening concrete slabs with prestressed CFRP laminates is researched in reference [141], focusing on the effect of "longitudinal steel reinforcement ratio, concrete strength, preloading level before strengthening, and adhesion between the CFRP laminates and the concrete," with particular focus on the preloading level. The study showed that prestressed EB CFRP laminates increased the ultimate capacity of the slabs by 64-119%.

3.3.1.2 Timber beams strengthened with composites

Several references were found that presented experimental investigations of flexural strengthening of timber beams. Much of the work that has been conducted on timber structures, experimentally and in the field, uses glass FRP. Experimental results of a study from 2000 conducted by the University of New South Wales showed that GFRP strengthened timber girders had a 25 to 50% increase in flexural strength and also an increase in ductility [142]. Another study showed that bonding on only the tension face resulted in a higher strength increase than bonding on both the tension face and compression zone surfaces [143]. Even though bonding on both sides yielded slightly stiffer members, the relative increase in stiffness was not justified based on the amount of material required, and therefore, FRP materials are not recommended to be used to increase a member's stiffness.

Lab tests of timber beams using a bidirectional carbon fabric as the primary strengthening material showed that the fabric led to significant increase in flexural and shear capacity, but only a nominal increase in stiffness [144]. This study also includes a conceptual discussion of allowable stress modification factors that could potentially be used to calculate the load bearing capacity of timber beams reinforced with carbon fiber.

The applicability of mechanically fastened FRP strips on timber members was investigated by Dempsey and Scott [145]. Results showed that FRP strengthening increased the members' ultimate moment, initial stiffness, and ductility over that of the control specimens. The effectiveness of the strengthening system was inversely related to the spacing of the fasteners. The investigation also revealed that the moisture content of the wood was a large factor in the member's ductility.

Wisconsin has many timber railroad bridges in need of repair due to heavier loads and deterioration. Stiffer pile caps are needed to prevent overloading of the timber piles. The University of Wisconsin successfully demonstrated that "Mechanically fastened FRP strips were effective in developing composite action in slender beams in flexure and truss action in short deep beams" which allows for loads to be more evenly distributed to the timber piles and prevents overloading [146].

3.3.1.3 Steel beams strengthened with composites

More recently, using FRP materials to strengthen steel girders has become popular in the research world. A review [147] is given of research conducted on "strengthening steel structures with FRP, stabilizing (or bracing) buckling-critical steel elements with FRP, and relieving fatigue or fracture-critical conditions." The use of FRP to repair of fatigue damaged steel girders and to reinforce buckling-critical steel elements was discussed previously in Sections 2.5.2 and 2.6.3, respectively.

In a comparison study, steel beams were strengthened in flexure with CFRP sheets bonded to the tension flange, CFRP plates bonded to the tension flange, and CFRP sheets attached to two ductile anchorage systems to determine the differences between the strengthening systems [148]. Test results showed that retrofitting with EB CFRP sheets or plates increased the load capacity of the beam but failure of the beam was less ductile as the composite debonded or ruptured. A ductile anchorage system was proposed as a solution to improve the ductility of the beams retrofitted with composites while maintaining the increase in capacity.

Steel-concrete composite girders were strengthened with prestressed EB FRP in a 2013 study [149]. The mechanical anchorage system was used to prestress the FRP laminate and the laminate then reacted directly against the steel girder. Innovative material steel fiber reinforced polymer (SFRP) sheets were used in comparison with CFRP plates and the prestressing system proved a practical method for both materials.

3.3.1.4 Summary of findings regarding flexural strengthening with composites

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.

- 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 strips and grid patterns, respectively.

- 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 the serviceability limit state.

- Prestressing can be directly applied to CFRP laminates, which can then be used to strengthen concrete girders or deck slabs while improving the serviceability limit state.

- 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).

- Bi-directional FRP fabric can increase flexural and shear capacity of a beam.

- The efficiency of MF FRP on timber beams was inversely related to the spacing of the fasteners.

- "Mechanically fasted FRP strips were effective in developing composite action in slender [timber] beams in flexure and truss action in short deep beams" [146].

- 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.

3.3.1.5 Field implemented flexural strengthening with composites

Hundreds of structures around the world have been strengthened in flexure through the use of FRP composites. Table 4 summarizes flexural strengthening applications that were reported in the literature. This table is not an exhaustive list of strengthening or rehabilitation projects around the world, but presents a sampling of installations that were found in the literature review.

The rehabilitation of three timber railroad bridges in West Virginia with GFRP wraps was reported to have increased the live load capacity by 20 percent and approximately doubled the member stiffness [162]. This retrofit extended the service life of the railroad bridges as they are now able to carry the heavier freight trains of modern traffic.

Load testing of an implemented retrofit showed that strengthening an RC integral abutment bridge with externally bonded CFRP decreased crack widths and concrete strains and improved transverse load distribution in the superstructure [166].

Table 4. Instances of Bridge Flexural Strengthening with FRP Composites

Location	Name/type	Year	Method	Reference	Additional Notes
China	---	1999	CFRP plate	150	First bridge strengthened by CFRP plate in China.
New York	RC T-beam bridge	1999	FRP laminate bonding	151 & 152	Laminates inspected after two years of service; bond still good.
Missouri	RC slab bridge	1999	CFRP sheet bonding	153	Successfully retrofitted without traffic interruption. Ongoing monitoring.
Canada	concrete bridges	prior to 1999	FRP plates/sheets	154	Summary of rehabilitation projects.
Quebec, Canada	Sainte-Emelie-de-l'Energie bridge	2000	CFRP bonding	155	Laminates bonded to the underside of beams; fibers in the longitudinal direction.
Oregon	Horsetail Falls Bridge	2000	FRP laminate bonding	156	---
Delaware	Steel girder bridge	2000	CFRP plates	157	Lab tests conducted at University of Delaware; implemented on I-95.
World Summary	RC infrastructure	prior to 2000	FRP plate bonding	158	Summary of strengthening with FRP and steel plates.
Missouri	PC bridge girder	2001	CFRP laminate bonding	159	Girder damaged by overweight truck impact. CFRP restored original structural capacity.
Alberta, Canada	Medicine River Bridge	2002	CFRP plates	160	Plates bonded to underside of three span deck in negative moment regions.
Sweden	Gröndals Bridge	2002	CFRP plates	161	Used to strengthen cracked concrete box beams service limit state. Arrested crack propagation in the webs.
West Virginia	timber railroad bridges	2002	GFRP wraps	162	Wrapped piles, pile caps, and stringers with resin soaked FRP fabric. Some stringers removed to be wrapped in GFRP, then reinserted.
USA	various members	prior to 2003	FRP laminates/PT FRP tendons	163	Summary of rehabilitation projects: concrete T-beams, box girders, steel truss members.
Kentucky	4 span RC bridge slab	2004	FRP bonding	164	---

Table 4. *continued…*

Iowa	steel girder bridges	2004	CFRP plates, PT FRP bars	165	2 IBRC projects. Plates bonded to bottom flange.
China	RC integral bridge	2005	EB CFRP	166	Longitudinal cracks formed due to lack of transverse reinforcement. Strengthening decreased crack widths and concrete strains and improved transverse load distribution in the superstructure.
Ohio	Hopkins and Clinton Street Bridges	2006	PT CFRP laminates	167, 168, & 169	IBRC project. Insignificant increase in strength.
Utah	State Street Bridge on I-80	2006	CFRP bonding	170	Bond tested in situ and found to still be effective after three years of service and environmental exposure.
Winnipeg, Canada	Main Street Bridge	2006	Prestressed CFRP sheets	171	Repaired impact damaged girder; restored flexural capacity and improved serviceability.
Australia	40 year old 4 span RC slab bridge	2007	CFRP strips	172	Strips bonded to top of the deck over the piers and on the deck soffit in the midspan regions to reduce high moments in both hogging and sagging.
Alberta, Canada	Quesnell Bridge	2008	FRP plates	173	Bonded to increase negative moment capacity. PT steel bars also used to improve stresses.
United Kingdom	concrete road/rail bridges	2010	EB FRP	174	Increase impact resistance of columns.
Kentucky	steel girder bridge	2010	UHM CFRP laminate	164	---
Pennsylvania	RC T-Beam Bridges	prior to 2012	EB FRP	175	Summary of rehabilitation projects.
China	overpass bridge	2013	EB CFRP	176	---
Japan	steel railroad bridges	2014	GFRP plates	177	Strengthening enhanced rigidity and reduced stress levels in the steel, thereby prolonging the service life.

Table 4. *continued…*

Kentucky	steel girder noncomposite bridge	2014	CFRP plates and shear studs	178	Shear studs provided composite action between the concrete deck and steel girders, making more efficient use of the added strength from the CFRP plates.

This is a case where retrofitting with composites benefitted the service load limit state as well as the ultimate load limit state.

The CFRP plate retrofit on the State Street Bridge on Interstate 80, in Utah, was tested three years after implementation to determine the bond durability [170]. The bond was found to still be effective after three years of service and environmental exposure. This data shows that composite repairs are durable and provides confidence for bridge owners to use composites for future bridge strengthening projects.

A steel girder noncomposite bridge in Kentucky was strengthened with CFRP plates, and shear studs were installed to provide partial composite action with the concrete deck to better utilize the composite repair [178]. The addition of composite action and the composite strengthening system led to a significant increase in the bridge's load-carrying capacity and decreased overall deflections. The load rating of the bridge was increased and the load posting on the bridge was removed. This case demonstrates successful implementation of two strengthening methods used simultaneously to produce a stronger bridge than either method could yield alone.

Externally bonded CFRP laminates were used to strengthen a PC girder in Missouri which had been damaged by vehicle impact of an over height truck [159]. Two of the girder's prestressing tendons were fractured due to the impact, resulting in a 10% decrease in flexural capacity of the girder. CFRP was successfully used to repair the girder and restore the flexural capacity, and the project led to "bridge strengthening protocol for consideration by the Missouri Department of Transportation" [159].

The first North American field application of prestressed CFRP sheets to repair impact damaged girders was implemented on a bridge in Winnipeg, Canada [171]. The repair was installed while temperatures were below 15°C and clamps were left in place for three weeks to compensate for curing time at low temperatures. The repair was designed in accordance with AASHTO LRFD code and successfully restored the flexural capacity of the girder and also improved the girder's serviceability.

Ohio experimented with post-tensioned CFRP rods on a four span steel girder, concrete deck bridge, and found that "The slight difference between the before and after deflections and strains was less than the variability that should be expected in the readings" [168]. They also experimented with fiberglass rods on a single span concrete T-beam bridge and had the same disappointing results [169]. The suggestion was made that using more rods with higher tensioning capacities could better distribute the force and provide a greater strengthening effect.

3.3.1.5.1 Innovative Bridge Research and Construction Program: flexural strengthening results

Table 5 lists the IBRC projects which used FRP materials to strengthen a bridge and is categorized by state. All the projects listed strengthened a structure's flexural capacity except for two projects conducted by Hawaii and Kentucky, which strengthened concrete structures for shear, and will be discussed in Section 3.3.2.2.1. The following members or structure types were strengthened in flexure through the IBRC projects: concrete T-beams, prestressed bulb-T-beams, arch bridges, concrete box beams, and steel plate girders [3].

Table 5. FRP Strengthening of Bridge Members in IBRC Projects

Member type	State	County	Project
Steel	DE		BR 119 on SR 82 (Ashland Bridge)
	IA		Route 141 over Willow Creek
	IA	Pottawattamie	I-A-92 over Walnut Creek
	OR		Sauvie Island Bridge
Concrete	AL		AL-97 Bridge over I-65
	AL		I-565, NBI Str. No. #015821
	AL		SR 81 over Uphapee Creek
	DE		BR 26 on Foulk Rd over Naaman's Creek
	GA	Cherokee	State Route 92 over Noonday Creek Bridge Rehabilitation
	HI	Honolulu	Salt Lake Blvd. Bridge over Halawa Stream
	KY		Louisa- Fort Gay Bridge
	KY		I-65 over Jacob, Broadway and Gray streets
	KY		KY Rt 3297 over Little Sandy River
	KY		KY 714 over Jeptha Creek
	MA		Franklin I-495 over MBTA Bridge
	MO	Morgan, Dallas, Crawford, Pulaski & Iron	X0596 Rte. Cover Creek, P0962 Rte. B over Creek, T0530 Rte. Mover Crooked Creek, Y0298 Rte. U over Creek, and X0945 Rte. Cover river
	NM		I-40 Tucumcari/ E. Interchange
	OH		Route 79 - Bridge COS-79-0955
	OH	Scioto	Bridge No. SCI-23-0166, US Route No. 23, City of Portsmouth
	PA	Union	SR 4012 over Shamokin Creek (same technology)
	PR		Bridges #2028 and #2029 on PR-52 over PR-1
	TX		Farm to Market Road 1362 over Sue Creek
	WV		East Street Viaduct carries CSX RR over WV Alt 14A
Timber	AL	Crenshaw	Surles Road Bridge over Bedsole Creek
	IA	Delaware	215 Avenue Bridge over Lime Creek
	ME		Fairfield, Emery Brook Bridge
	WA		Ever's Bridge

Note: Adapted from *Project case studies for IBRC and IBRD Programs*, by D. Paterson et al., 2012, FHWA unpublished internal document, p.678-679.

Some advantages of rehabilitating flexural bridge members with composite materials were discovered by the IBRC/IBRD programs first hand [3]. 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 again. 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 also encountered by the IBRC/IBRD installations [3]. 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, the installation costs are typically greatly reduced once new materials are 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 general lessons learned by the IBRC/IBRD projects led to the following guidance and recommendations [3]. 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 such 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.

Some projects investigated the material properties and behavior of the composite material in use [3]. The epoxy bond of an FRP wrap on a masonry arch in Colorado was fire tested and found to break down and deteriorate at 446°F. Oregon conducted evaluation tests to determine the bondline strength for epoxy bonded FRP to steel beams and found it to be greater than 900 psi, which is more than two times the minimum of 400 psi bondline strength required for concrete strengthening. Experimental testing conducted at the University of Delaware concluded that concrete box beams reinforced with CFRP plates will fail in a more brittle manner than concrete box beams reinforced with steel rebar. It was recommended that brittle failure of FRP retrofits be studied further, and Section 2.6.4 of this paper discusses the research conducted on this topic. Iowa reports that more strength might possibly have been gained on one of their projects if the structure had been jacked before applying FRP plates to the steel beams. This is probably true, but introduces another step in the rehabilitation process involving large cranes that are otherwise not needed for strengthening with composite materials.

3.3.2 Shear Strengthening with Composites

Different FRP composite materials are used to strengthen structures in shear, including FRP sheets or strips, U-shaped stirrups [155], L-shaped plates [179], near surface mounted (NSM) laminates [38] or NSM rods [41], and shear spikes [180]. Shear strengthening with FRP materials has been implemented on bridge girders, bridge columns, and concrete deck slabs. Bridge girders which have been strengthened in shear include concrete T-beams, channel beams [181], prestressed girders [164], and timber beams [182]. FRP materials can also be used to strengthen a member in flexure and shear at the same time.

3.3.2.1 Laboratory testing experimental results of shear strengthening

Many experiments have been conducted on the shear behavior of RC beams strengthened with FRP composites, and a summary of the research up to 2003 is given in [183]. A compilation of lessons learned from experimental research in the UK is given by Ibell [80]. "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" [80].

Using FRPs to strengthen concrete slabs has mostly been conducted to increase flexural capacity, but FRPs can also be used to strengthen concrete slabs in shear. The strips can be preinstalled or bonded in the field for strengthening. One study reports that installing CFRP grid sections vertically through the deck "is capable of changing slab failure from the shear mode to the flexure mode" [184]. This study used special spacers when casting the deck to leave holes for the CFRP grid to be inserted and epoxied to the structure, and found that by increasing the number of CFRP grids, punching shear failure could be avoided. Other studies use CFRP plates bonded to the soffit of the deck to increase shear capacity. Sim and Oh propose that yield line theory is applicable to bridge decks strengthened with FRP, but a punching shear theory should be developed to reflect the "restraint effects that are due to the strengthening material" [185].

Continued research is being conducted to determine the shear behavior of concrete structures with FRP reinforcement, especially when the structure is subjected to fatigue loading. One study investigated concrete slabs strengthened with a combination of post-tensioned FRP tendons and non-prestressed GFRP bars [186]. This combination led to improved fatigue performance of the GFRP bars, but the governing failure mode may still be shear, so additional innovative shear reinforcement was required since conventional stirrups are not practical for slab bridge construction. Test results showed that FRP double-headed shear bars provided excellent shear reinforcement and good fatigue performance and were easy to install in the shallow concrete members.

Many concrete channel beam bridges in Arkansas were designed without shear reinforcement. In 2004, the University of Arkansas developed a technique of using FRP strips as external stirrups to strengthen these structures in shear, preventing the formation of full diagonal cracks between strips and ensuring flexural failure instead of sudden shear failure [187]. In 2011, shear retrofitting methods of FRP bonding, epoxy spray-on coating, and shear bars installation were compared for the retrofit of a precast, non-prestressed, channel beam bridge, and "implanting shear bars into each precast channel beam stem was found to be the optimal retrofit based on improved beam strength, installation ease, and economics" [188].

Full-scale concrete deck girders were strengthened with FRP U-wraps and showed that "the CFRP provided additional shear strength and deformation capacity, even with large debonded regions prior to failure" [189]. The controlling failure mode was "debonding of the U-wrapped CFRP strips" [189].

A study was conducted on forty-two year old retired AASHTO I-shaped RC girders to investigate the best orientation for shear strengthening CFRP strips. The study indicated that a scheme of vertical strips with a horizontal anchoring strip was most effective in resisting the applied shear [190].

An experiment was conducted to determine the shear strength contribution of full FRP wraps on RC beams [191]. An RC beam strengthened in shear with a bonded FRP full wrap usually fails due to rupture of the FRP, "commonly preceded by gradual debonding of the FRP from the beam sides" [191]. The experiment included beams which had bonded FRP full wraps and beams with FRP full wraps left unbonded to the sides of the beam. "Test results show that the unbonded FRP wraps have a slightly higher shear strength contribution than the bonded FRP wraps, and that for both types of FRP wraps, the strain distributions along the critical shear crack are close to parabolic at the ultimate state" [191]. The FRP ruptured at considerably lower strains than rupture strains of flat tensile coupons, possibly due to the dynamic debonding and deformation of the FRP wraps caused by the movement of the composite on either side of the shear crack.

In a 2014 study, research was conducted to determine the effect of embedment length for L-shaped CFRP plates strengthening concrete girders [192]. Usually, grooves are cut into the beam flange to fully embed the vertical portion of the L-shaped CFRP plate, but sometimes obstacles, such as rebar prevent full embedment. This study compared beams with fully embedded, partially embedded and surface bonded L-shaped CFRP plates and EB FRP sheets. Results show that partial or full embedment of the L-shaped CFRP plate is much more effective in strengthening concrete beams than no embedment or EB FRP sheets and therefore the preferred method if possible [192].

A closed RC railroad bridge located in Sweden was tested to failure in situ to develop an FE model which would "assess the effectiveness of various strengthening schemes to increase the load-carrying capacity of the bridge" [193]. The bridge was strengthened in flexure with NSM FRP bars in an effort to cause shear failure, as this was the focus of the model. The bridge failed in "an interesting combination of bending, shear, torsion, and bond failures at an applied load of 11.7 MN (2,630 kips)" [193]. The model developed was compared to the Swedish code, as well as codes from Canada (CSA), Europe (EC2), and the United States (ACI). The predicted value calculated by each different code was divided by the bridge capacity found from the test to give a ratio of P_V/P_{Test}. Differences in the ratios are due to the way the shear truss mechanism is applied in each code. Two values were calculated for the EC2 because it uses the variable truss angle model, using a minimum angle of 22°, and a maximum angle of 45°, giving ratios of 0.31 and 0.78, respectively. In an effort to most accurately represent the capacity of the bridge, the angle closest to the angle given by the FEA model is adopted by EC2. The ACI code uses a conservative assumption that the compression strut is at a 45° angle, and thus gives a ratio of 0.66. The CSA code uses a simplified version of the modified compression field theory (MCFT) and the angle of the compression struts was calculated through iteration to be 38°, giving a ratio of 0.65. The developers of this FEA model note that the CSA code varied from the test value possibly due to the fact that the MCFT was developed based on a concrete member with steel reinforcement only, whereas, the tested beam was also reinforced with externally bonded CFRP. As each code is shown to vary from the tested capacity of the member, the developers of the FEA model recommend that bridges be field tested for an accurate capacity assessment prior to strengthening.

A new method called embedded through-section (ETS) technique has been developed to increase the shear capacity of a concrete beam, and it provides a better bond than NSM and EB methods because it relies on the core of the beam rather than the concrete cover [194]. Experimental test results from [194] "confirm the feasibility of the ETS method and reveal that the performance of the beams strengthened in shear using this method is significantly superior compared to the performance of beams strengthened with EB and NSM methods."

Several lab experiments have been conducted to study the effect of shear strengthening with FRP materials on timber girders. One study found that diagonal layup of GFRP sheets was more effective than vertical layup to increase shear capacity of timber stringers with horizontal splits at their ends [182].

A relatively new method of shear strengthening timber stringers of railroad bridges is by inserting shear spike fiberglass rods through areas of damage. The spikes are inserted through predrilled holes in the top of the member, perpendicular to the bending axis, and the holes are filled with epoxy-resin adhesive to bond the spikes to the timber and to fill any adjacent cracks or decay voids [180]. Experimental testing on full scale timber members showed that “FRP rods are highly effective in restoring the flexural stiffness and shear strength of deteriorated timber members” [180]. A follow-up experiment on timber chord members demonstrated that timber beams with advanced deterioration experienced a larger increase in strength from shear spike rehabilitation than beams with only modest deterioration, suggesting that this rehabilitation method has great potential for in situ repairs for timber bridges [195].

The following is a summary of key findings regarding shear strengthening using composites.

- CFRP grid sections can be installed vertically in concrete deck slabs to change the failure mode from shear to flexure.
- CFRP plates can be bonded to slab soffits to increase shear capacity.
- FRP double-headed shear bars provided excellent shear reinforcement , good fatigue performance, and were easy to install in shallow concrete members.
- 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.
- When using a full wrap to strengthen a girder in shear, it is recommended that the wrap be left unbonded to 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.

- 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 method is a new shear strengthening method that relies on the core of the beam which provides a better bond than EB or NSM.
- Diagonal layup of EB FRP sheets is more effective than vertical layup when strengthening timber beams in shear.
- Shear spike fiberglass rods are effective in strengthening timber railroad bridge ties in shear.

3.3.2.2 Field implemented shear strengthening with composites

Several references were found which detail the field implementation of FRP materials to strengthen bridge components in shear and are listed in Table 6 below. Several bridges listed below were also mentioned in the flexural strengthening section, as the bridge was strengthened in both flexure and shear.

One field application in the UK compared FRP laminates and external prestressing on the same structure and found that FRP laminates seemed to be the optimal strengthening method for shear regions of RC structures while external prestressing tendons were more optimal for strengthening the bending regions of the structure [196].

One reference was found which details the implementation of FRP materials in Ontario to strengthen a bridge girder in shear, which had been damaged by truck impact, and load testing was used to verify the strengthening effect of the repair. Load testing also verified that flexural strengthening was not needed because the flexural capacity of the girder had not been affected by the impact [202].

Table 6. Instances of Bridge Shear Strengthening with FRP Composites

Location	Name/type	Year	Method	Reference	Additional Notes
Canada	concrete bridges	prior to 1999	FRP plates/sheets	154	Summary of rehabilitation projects.
Quebec, Canada	Sainte-Emelie-de-l'Energie bridge	2000	U-shape GFRP stirrups	155	Increased capacity to meet loading requirements.
Kentucky	3 span PC bridge	2001	CFRP fabric	164	---
USA	concrete box girders	prior to 2003	FRP laminates/PT FRP tendons	163	Summary of rehabilitation projects.
United Kingdom	RC bridge	2003	FRP bonding	196	PT bars also used for flexural strengthening.
United Kingdom	Tay Road Bridge	2004	Aramid (Kevlar) FRP bonding	197	Kevlar FRP was wrapped around the bridge columns to increase shear stiffness and resistance to vehicle impact.
Hawaii	Salt Lake Boulevard Bridge	2004	L-shaped CFRP stirrups	198	IBRC project. CFRP stirrups applied over existing shear cracks. Controlled crack width and prevented crack propagation.
Queensland, Australia	Tenthill Creeks Bridge	2007	FRP plate bonding	199	Rectangular, cracked concrete headstock strengthened in shear and bending in accordance with AS 3600.
Kentucky	Washington and Nelson County Bridges	2007	Steel FRP sheet bonding	164	Steel FRP sheets were bonded to the vertical and bottom faces of cracked variable depth RC continuous girders.
Alberta, Canada	Quesnell Bridge	2008	FRP fabric	173	Shear capacity increased to meet new design loads.
Melbourne, Australia	West Gate Bridge	2011	EB CFRP	200	Both unidirectional and bidirectional fabrics used together to successfully transfer shear and torsional forces.

Table 6. *continued…*

New Brunswick, Canada	Trout Brook Bridge	2012	unidirectional GFRP U-wrap	201	Outer 5 m of each girder was strengthened to increase load rating to meet heavier traffic demands.
China	overpass bridge	2013	EB CFRP	176	---
Ontario, Canada	RC girder	2013	FRP sheets	202	Used to strengthen impact damaged girder. Load tested to verify strengthening effect and no need for flexural strengthening

In the UK, the columns of the Tay Road Bridge were wrapped with aramid, also known as Kevlar, FRP sheets to increase their shear stiffness to better withstand vehicle impact loading [197]. Kevlar FRP has also been used to strengthen and stiffen concrete beams and slabs and to strengthen other bridge supports to resist vehicle impact [4].

The Washington and Nelson County bridges in Kentucky are five-span and three-span bridges, respectively, built in 1955 with continuous RC girders that developed diagonal cracks at the transition between variable and constant depth regions. Steel FRP sheets were chosen as the strengthening material for their "high tensile strain, excellent conformability due to its flexibility, and bondability" [164]. The steel FRP sheets were bonded to the vertical and bottom faces of the girders in the transition region to restore the girder capacity and control crack openings. The cracks were filled with epoxy prior to the repair and crack gauges were installed "to monitor any potential movement and evaluate the effectiveness of the retrofit" [164].

The West Gate Bridge in Melbourne, Australia is a unique bridge that curves in opposite directions at either end and also crests in the middle. This bridge was strengthened with EB CFRP in 2011 using unidirectional and bidirectional fabrics together with mechanical substrate strengthening. The combination of technologies allowed for better utilization of the strengthening material and successfully enabled the transfer of combined shear and torsional forces [200].

3.3.2.2.1 Innovative Bridge Research and Construction Program: shear strengthening results

As previously stated, few IBRC projects focused on shear strengthening. Some projects were able to increase shear resistance with the same FRP repair that increased the flexural strength of the structure, such as the Alabama I-565 repair, and the Colorado arch bridge repair. The IBRC report cautions that the corners of U-wraps used for shear strengthening must be rounded to prevent localized stresses in the FRP which would lead to delamination [3].

An IBRC project in Hawaii used L-shaped CFRP plates to purposefully strengthen the Salt Lake Boulevard Bridge in shear, specifically focusing on the effectiveness of the retrofit over existing shear cracks under cyclic loading. These CarboShear L-shaped plates were designed in Switzerland [203]. Experimental tests were run in a laboratory to verify that the plates would provide the necessary strength when applied over existing shear cracks [198]. Fiber reinforced cementitious composite (FRCC) filler blocks were used to make the prestressed T-beam rectangular, to allow the attachment of the FRP L-shaped shear stirrups. During cyclic loading the stirrups contributed significantly to control the width of the existing shear cracks and prevented crack growth. The CarboShear-L stirrup retrofit system also increased the beam stiffness and reduced beam deflections. When the beam was loaded to failure, the L-shaped stirrups prevented shear failure and the beam failed in delamination of the flexural FRP strips bonded to the soffit of the beam. Thus, the lab testing was successful and the L-shaped stirrups were installed on the Salt Lake Boulevard Bridge. Monitoring of the bridge immediately after the retrofit showed that the stirrups significantly controlled the width of existing cracks and also increased beam stiffness. Unfortunately, after the retrofit, large cracks were found in the backspans of the bridge and the bridge was removed from service, thus no long term data was obtained [3].

Instead of L-shaped stirrups, Kentucky simply bonded FRP fabric to the web and bottom flange of many precast concrete girders to strengthen their shear capacity. The girders had formed shear cracks at the ends which were propagating and increasing in number. The FRP fabric halted the crack growth and prevented future cracks from forming [3]. The technology was reported to be 'highly effective' and was used to strengthen precast concrete beams at over 100 locations across the state of Kentucky. Those who implemented the retrofits caution that surface preparation and proper installation of the FRP fabric is crucial to provide a strong bond and prevent delamination, and to ensure the success of the repair.

3.3.3 Increasing Live Load Capacity with Lightweight Composite Decks and Deck Strengthening with Composites

Iowa State University is currently conducting a project to summarize the long-term field performance of innovative bridge projects which were implemented over the past decade. They will document the lessons learned and the advantages (or lack thereof) provided by the innovative bridge technologies used [204]. The University of Central Florida, Orlando and the Florida International University, Miami, are conducting a project to develop "innovative modular high performance lightweight deck options that lend themselves to accelerated bridge construction (ABC)" [205]. The deck systems will be prefabricated and make use of ultra-high performance concrete (UHPC), high-strength steel (HSS), and FRP as appropriate. Phase one of this project identified the possible materials, and phase two conducted the necessary experimental studies for design and implementation of the deck systems [206].

There are several different types of FRP decks. One difference between deck types is the core configuration which can be honeycomb sandwich (Figure 10), solid core sandwich (Figure 11), or pultruded hollow core sandwich (Figure 12) [207]. The materials used to construct the decks can also vary from fiberglass to glue-laminated wood panels.

Figure 10. Honeycomb sandwich configuration. *Figure 3.3.1-1*. Honeycomb sandwich configuration. Reprinted from *Field inspection of in-service FRP bridge decks*, by N.M. Telang et al., 2006, *NCHRP 564,* p.19. Copyright [2006] by Transportation Research Board.

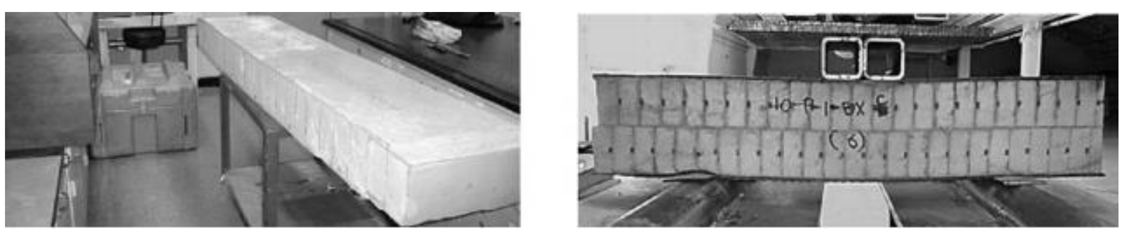


Figure 11. Solid core sandwich configuration. *Figure 3.3.2-1.* Solid core sandwich configuration. Reprinted from *Field inspection of in-service FRP bridge decks*, by N.M. Telang et al., 2006, *NCHRP 564*, p.19. Copyright [2006] by Transportation Research Board.

FRP deck panels offer many benefits over traditional decks. “As compared with cast-in-place concrete bridges [sic] decks, they weigh 80% less, can be erected twice as fast and have service lives that may be two to three times greater” [208]. They can be erected so quickly because the panels are prefabricated, which means no

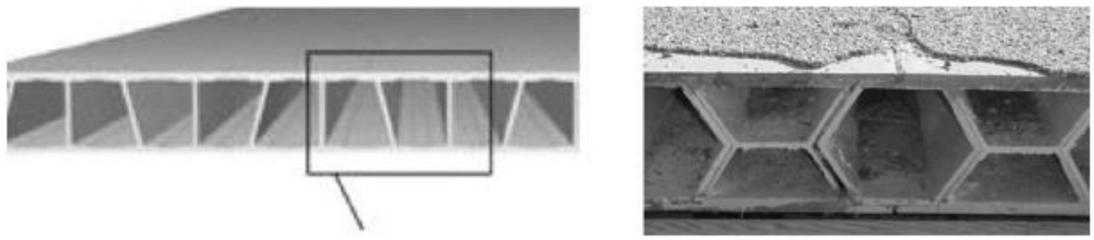


Figure 12. Pultruded hollow core sandwich configuration. *Figure 3.3.3-1.* Pultruded hollow core sandwich configuration. Reprinted from *Field inspection of in-service FRP bridge decks*, by N.M. Telang et al., 2006, *NCHRP 564*, p.20. Copyright [2006] by Transportation Research Board.

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.

3.3.3.1 Field implemented lightweight composite decks and deck strengthening with composites

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. Other bridge decks that were cracked or damaged have been repaired and strengthened using composite materials. Table 7 gives a summary of lightweight deck and deck strengthening applications found in the literature review.

FRPs are being used in the railway industry to strengthen railway bridges, as deck platforms, as main load bearing decks, and one application of FRP as a "secondary decking system for carrying railway live loading" [223].

A bridge in Missouri had formed a one inch wide longitudinal crack along the concrete deck and was successfully retrofitted with externally bonded FRP laminates after the crack was injected with epoxy to allow continuity in the cross section [224].

The bridge deck soffits of spans 8 and 9 of the Watson Wash Bridge in California was repaired with CFRP composites and then monitored for integrity and effectiveness. "A reliability index is used for combining the effects of material variation, CFRP composite degradation, and measured stiffness changes from the field to assess the service life of a FRP rehabilitated structure" [221].

Table 7. Instances of Lightweight FRP Decks and Bridge Deck Strengthening with FRP Composites

Location	Name/type	Year	Method	Reference	Additional Notes
Kentucky	Suspension Footbridge	1999	GFRP Superstructure	164	Longest FRP suspension bridge in the world: 420 ft.
Delaware	Through truss bridge	2000	GFRP Deck Panels	209	Historical preservation project of timber truss bridge.
Japan	Highway ramp bridge	2000	Spray Polymer Cement Mortar	210	Concrete deck slab strengthened with bottom-side thickening method, using spray polymer cement mortar.
New York	various bridges	prior to 2001	FRP Decks	211 & 212	Summaries of rehabilitation projects. Suggests when use of FRP decks is most appropriate.
Maryland	Through truss bridge	2002	FRP Deck	213	Design detail modifications for roadway skew and roadway crown accommodation. Composite action with steel stringers.
New York	Truss bridge	2003	FRP Deck	214	FRP deck is 80% lighter than deteriorated concrete deck it replaced. No composite action with girders.
Washington	Chief Joseph Dam Bridge	2003	FRP tube Deck	215	IBRC Project. Timber truss bridge. Inefficient lateral load distribution between deck panels.
Winnipeg, Canada	Red River Bridge	2003	GFRP reinforced concrete deck	216	Second-generation steel-free deck slab.' Structural Health Monitoring installed.
Colorado	O'Fallon Park Bridge	2004	GFRP Honeycomb Deck	217	IBRC Project. Governing failure mode of sandwich panels is delamination of upper face from core.
Oregon	Movable bridge	2005	FRP Deck	218	ODOT recommends flexible attachment details and wearing surface.
Virginia	Cast iron Thru-truss bridge	2006	FRP Cellular Deck	219	Replaced concrete deck to reduce self-weight and raise load carrying capacity. Panel level connections made with bonded tongue and groove splices with scarfed edges.
Louisiana	Pierre Part Bridge	2007	FRP wrapped Balsa Wood Deck	220	IBRC Project. Removed from service after several years of service yielded top surface delamination.

Table 7. *continued…*

California	Watson Wash Bridge	2008	EB CFRP	221	Monitored to assess integrity of retrofit. Reliability index used to assess service life.
Friedberg, Germany	Friedberg Bridge	2008	GFRP Deck Panels	222	First GFRP road bridge in Germany. Composite action between deck and steel girders.
United Kingdom	railway bridges	prior to 2009	FRP strips, Decks, and Platforms	223	Also first application of FRP secondary decking system for carrying railway live loading.
Missouri	RC steel-free bridge	2009	EB FRP	224	No transverse steel. Epoxy injection of one inch wide longitudinal crack to ensure continuity.
United Kingdom	concrete road/rail bridges	prior to 2010	EB FRP	174	Increase bending strength of decks.
Washington	Steel girder bridge	2010	GFRP Tube Deck	225	Large deflections due to top plate delamination. Retrofitted with screws.
New York	steel girder bridge	2012	FRP trapezoidal Tube Deck	226	No composite action. Deck deflects more than concrete decks.
Pennsylvania	steel girder bridge	2013	FRP Deck	227	Shear studs installed for composite action. FE analysis investigates dynamic response.

A concrete deck slab on a highway bridge was strengthened in Japan using the slab bottom-side thickening method, using spray polymer cement mortar (PCM) [210]. This technique was innovative because the slab bottom-side thickening method is usually completed by hand using trowels to apply the PCM. Strengthening was needed to halt crack growth due to repeated overloading from heavy trucks and prevent punching shear fracture. Results of load testing before and after strengthening were given to confirm the effect of the strengthening method using spray PCM.

The first overpass bridge with an FRP deck in Germany was constructed in Friedberg, in 2008 [222]. Building upon lessons learned in construction of bridges with

FRP decks in the United States, Japan, and Europe, this bridge utilizes the composite action between the FRP deck and the steel girders. To further embrace durable bridge construction, bearings and expansion joints were omitted in the bridge, which also made the FRP deck visible to passers-by.

New York constructed an FRP bridge deck as an experimental project to improve the load rating of a 50-yr old truss bridge in Wellsburg [214]. Since the FRP deck was 80% lighter than the deteriorated concrete deck it replaced, the live load capacity of the bridge was increased, and the service life was extended. Load testing was conducted to determine the effectiveness of joints in load transfer and whether or not the deck and superstructure acted compositely. Results showed that the joints were only partially-effective in load transfer between panels and that there was no composite action between the deck and superstructure. Test results also showed that “Peak strains under the test loads were only a very small fraction of the ultimate strength of the FRP deck” [214].

A GFRP deck on a steel girder bridge in Washington was constructed of GFRP tubes adhesively bonded to a top and bottom plate, and was found to have large deflections after nine months of service in the field [225]. These deflections were caused by the tubes delaminating from the top plate. To retrofit the deck, screws, coated with a two-part epoxy that mixed when they were driven, were used to reattach the tubes to the top deck. This repair was still performing well when the paper about the project was written.

A trapezoidal pultruded FRP deck was installed on a steel girder bridge in New York [226]. Load tests show that composite action was not achieved by the girder-deck connections. The deck deflections are larger than typically allowed, but the deflections are “confined to the localized area of the wheel load and would not affect bridge users”

[226]. O'Connor offers a summary of New York's experiences implementing FRP decks including valuable lessons learned and provides recommendations for when FRP decks are most applicable [211].

3.3.3.1.1 Innovative Bridge Research and Construction Program and other implementations: lightweight deck results

This section covers lessons learned and provides cautions concerning potential problems during or after installation of lightweight decks from experiences gained in the field. The first two projects presented cover aluminum bridge decks and sandwich plate system bridge decks from the IBRC program. The remainder of the information presented was collected from FRP deck projects of the IBRC program [3].

Kentucky reported building two lightweight aluminum bridge decks as part of the IBRC program. The reduced dead load led to an increase in the bridge's live load capacity, and the twelve deck panels took only two hours to place and traffic was opened on the bridge while the underside of the deck was attached to the steel girders. After three years of monitoring one project, no signs of deterioration or damage were noted. The second project's deck placement took longer than expected due to the layout of the truss bridge floor beams and stringers, because detailed bridge plans were not available. Monitoring of the second project is ongoing. The panels were very expensive, which may limit their use to steel girder bridges in congested areas. Kentucky suggests that the construction workers be trained to lift and place the aluminum deck panels and conduct practice runs prior to placing the actual bridge.

Texas reported the use of a sandwich plate system (SPS) bridge deck for an IBRC project. The SPS is a composite material technology comprising two metal plates and an elastomer core, and offers an alternative to steel and concrete decks. The project experienced many negative results, but few are attributed to the SPS deck technology. The deck surface was uneven, due to distortion from the welding process. It was recommended that the prefabricated panels be smaller to decrease fit-up problems in the field and weld-induced distortion. The camber of the deck was excessive, possibly also due to the weld distortion, or because of incorrect beam camber. The proper overlay material to meet specification requirements was difficult to identify, and the one selected was reported to be peeling up in service. The SPS technology was selected to decrease construction time, and the deck took only three days to install, which was considered successful. However, a several month delay occurred after the deck was constructed due to the selection of the overlay material. Texas Tech University entered a contract with TxDOT to instrument and evaluate the in-service behavior of the bridge.

Table 8 gives a summary of the IBRC projects using FRP decks. Some IBRC projects also used FRP beams, which were previously discussed in Section 2.6.1.

An IBRC project placed an FRP tube deck on the Chief Joseph Dam Bridge in Bridgeport, Washington, and found that lateral load distribution between the tubes within the panels was inefficient. The asphalt wearing surface overlay was cracked at most deck panel joints and the deck joints were deteriorated "to extent that many required complete replacement within the first 18 months of construction" [215].

The Oregon Department of Transportation (ODOT) installed FRP decks on two movable bridges near Astoria in 2002 (one of which was an IBRC project) and one in Florence in 2005. The first lesson learned was that asphalt concrete does not bond well to FRP deck surfaces. The wearing surface slid off in a sheet during a prolonged lift test. The bridges in Astoria experienced failure of the connecting details and cracking of the wearing surface because the cementitious grout and epoxy polymer cement

Table 8. IBRC Projects using FRP Decks

Composite Structural Element	State	County	Project
GFRP panel	CO	Jefferson	Denver Parks O'Fallon Park Bridge over Bear Creek
FRP Deck, monitoring	FL		Hillsboro Canal Bridge
FRP Deck	HI	Maui District	Honolua Stream Bridge
FRP Deck	IA	Scott	53rd Ave. over Crow Creek Bettendorf
FRP Deck	IA	Johnson	4th Ave. over Ralston Creek
FRP Deck	IA	Winndshiek	Iowa 24 over Goddard Creek
GFRP Deck	IL		Jacksonville, S Fayette Street over Town Brook
GFRP Deck	IL	St. Clair	Pleasant Ridge Rd. over Little Canteen Creek
FRP Deck	IN	Tippecanoe	County Bridge #153
FRP-wrapped Balsa wood	LA	Franklin Parish	Louisiana Route 70, Bayou Pierre Part
FRP Deck	MD	Harford	Rehabilitation of Bridge No. 12016 on MD 24 over Deer Creek
FRP reinforced glulam deck panels	ME		Union-Washington Skidmore/Medomak Bridge
FRP reinforced glulam deck panels	ME		Municipal Pier in Milbridge
GFRP Deck	MO	Greene	FR-148 Bridge over Pearson Creek
GFRP Deck	NC		Bridge 00890022 on New Salon Rd.
FRP Deck	OH		Route 49-0103, Dayton
FRP Deck	OH	Huron	FA-114-01.64 over stream
FRP tube deck	OH		Stelzer Road, Columbus
FRP Deck	OR	Clatsop	State Hwy #105 MP4.78 & MP 6.89
GFRP Deck	OR	Multnomah	The Broadway Bridge, NW Broadway over Williamette River
FRP Deck	PA	Bedford	T-565 over Dunning Creek
FRP deck slab	PA	Susquehanna	State Route 1037 over Dubois Creek
FRP Deck	PA	Butler	State Route 4012 over Slippery Rock Creek

Table 8. *continued…*

FRP Deck	PA	Lycoming	TR -776 Bridge over English Run
FRP Deck	PR		Bridge 281 at PR -139 [Km 2.5)
FRP Deck	SC	Spartanburg	S-42-655 over Norfolk/Southern Rail Road
FRP Deck	VA		Hawthorne Street over C&O RR
FRP Deck	VA		Troutville Weight Station Ramp
FRP Deck	WA		Chief Joseph Dam Bridge
FRP Deck	WV		Market Street Bridge
FRP Deck	WV	Cabell	Howells Mill Bridge CR 1 over Mud River

Note: Adapted from *Project case studies for IBRC and IBRD Programs*, by D. Paterson et al., 2012, FHWA unpublished internal document, p.678-679.

overlay were too rigid to allow for the larger deflections associated with FRP decks. The IBRC project FRP bridge in Astoria was in service for 10 years before being replaced by another FRP deck. The FRP deck itself was reported to have performed well, but had to be replaced "due to the failures in the details and bonded joints" [3]. When the bridge in Florence was constructed, neoprene sheets, large structural blind fasteners, and a urethane polymer concrete overlay were used instead. These attachment details and wearing surface are strong but more flexible, were used on the Astoria bridge replacement, and are recommended by ODOT for future installations [218].

Louisiana constructed an FRP-wrapped balsa wood bridge as an IBRC project and monitored the bridge for several years. After several years of service, a delamination was observed and the deck was removed from service and replaced. The delamination was caused by the top FRP surface shifting during fabrication, causing less epoxy to be infused than was needed [220].

The GFRP deck installed on the O'Fallon Park Bridge west of Denver, Colorado as an IBRC project was designed with a safety factor of five against failure and satisfied the deflection limits stipulated in the design provisions [217]. The University of Colorado at Boulder evaluated the deck design and determined that due to the "material orthotropy of the panel and the localized bending effect caused by the soft core can reduce the effective bending width by 25% compared to a homogenous isotropic panel" [217]. The study also confirmed that the governing failure mode for GFRP Honeycomb decks is delamination of the upper face from the core and should be a major consideration in the design process [217]. One research study suggested that using a fabric wrap to repair the delaminated deck is effective in restoring and increasing the original strength of the deck by 65% [228].

Maryland used IBRC funds to replace the deteriorated concrete deck of a through truss bridge with an FRP deck to increase its live load capacity [213]. Many design modifications were necessary to address "severe roadway skew, roadway crown accommodation, selection of proper roadway overlay, traffic railing attachment and attachment of the deck to the framing system" [213]. Since this was the first application of an FRP deck in Maryland, the bridge was monitored long-term for the effects of live load on the bridge system. An FE model was also developed. "Dynamic effects of the FRP system, composite action between steel stringers and the FRP deck as well as the effective width and distribution factors of stringers were obtained and compared with the AASHTO specifications" [229].

Iowa experimented with FRP deck panels with Styrofoam cores in their IBRC projects and only found negative results, reporting that the panels delaminated due to the Styrofoam deteriorating under water exposure. Water infiltrates many FRP deck types and can fill up the voids in the panels. This increases the weight of the deck in addition to deteriorating the panels. Drain holes are a simple solution to this problem, and it is recommended that they be drilled in FRP decks at the time of installation to prevent water damage.

Several other states implemented fiberglass deck panels in their IBRC projects and saw very positive results. Another common implementation was FRP-glulam decks. Glulam is an abbreviation for glue-laminated timber. FRP plates were bonded to the underside of glulam panels to increase their strength and protect the timber from the environment. Maine reports that FRP-glulam panels are more ductile than glulam panels and have a 35.7% higher failure load. It was also discovered that exposure to Chromated Copper Arsenate (CCA) preservative reduced the longitudinal tensile strength of unidirectional composite laminates.

North Carolina was able to achieve full composite action between fiberglass deck panels and steel girders, while Pennsylvania was only able to achieve limited composite action between FRP decks and steel girders, and Iowa had limited composite action with an FRP deck and RC girders. Holes are precut in the FRP deck panels where shear studs will be attached to the girders to create the composite action. After the panels are placed, the holes are grouted. West Virginia reported difficulty in grouting the holes. One project reported that the grout settled into the panels. Another report stated that tie downs had to be placed on 2 ft. centers to correct panel deflections caused by heat from the sun, which then required coordination when grouting the panels.

Virginia conducted laboratory experiments on FRP cellular, also known as Strongwell, deck systems and reported that the panels show linear elastic behavior up to the design service load and test results revealed an average deflection of L/664. The top plate and top flange of the tube failed in weak-axis bending, with cracking parallel to the tube webs, at an average first failure load of 100 kips, which is about five times the computed design service load. The deck system was then used to rehabilitate a historical cast iron thru-truss structure and two other IBRC projects.

The following is a summary of key findings regarding FRP 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.
- Styrofoam core is 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.
- The soft core of GFRP panels can reduce the effective bending width by 25% compared to a homogeneous isotropic panel.

- FRP-glulam panels are more ductile than glulam panels and have a 35.7% 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 deck exhibits linear-elastic behavior up to design service load and has average deflection of L/664.

3.3.3.2 Ongoing research on lightweight composite decks

Due to the novelty of composite decks, many areas are still being investigated including composite action with the bridge superstructure, connectors between the deck and stringers, connectors between deck panels, performance of decks under load and environmental conditions, and optimal material for core assembly.

Composite action is an ongoing concern for bridges with FRP decks, as composite action provides a much higher load capacity, but force transfer between the FRP deck and traditional material superstructure is a challenge. A demonstration bridge was constructed in Ohio for the purpose of developing composite action between an FRP deck and steel girders to carry superimposed dead load and live load [208].

The connection between composite decks and steel or concrete girders is a major concern, because a good connection is necessary for composite action. Caltrans and the University of California San Diego are researching these connections [230]. Xu Jiang conducted his doctoral thesis on the durability of FRP-to-steel adhesively-bonded joints, experimenting with the effect of different surface preparations and the performance of the bond under different tensile and shear loads [231].

The best method to join FRP panels to each other is under investigation. An adhesively bonded tongue and groove splice with scarfed edges was used to join FRP deck panels on a truss bridge in Virginia [219]. Laboratory tests of a representative model showed that “no crack initiated in the joints under service load and no significant change in stiffness or strength of the joint occurred after 3,000,000 cycles of fatigue loading” [219]. However, adhesive bonding must take place on-site and requires curing time, which detracts from the benefit of rapid construction gained by using FRP panels. A novel joint configuration for panel level connections as an alternative to adhesive bonding is proposed in study [232].

The dynamic response of an FRP deck attached to steel girders was investigated through an FE model of a bridge in Pennsylvania [227]. The deck was installed with shear studs to create composite action between the deck and girders. Static load testing of the bridge was conducted to verify the FE model before the bridge was studied under dynamic loads. The static and dynamic responses in the partially composite model were greater than the corresponding responses in the fully composite model. The dynamic response in the partially composite model also lagged behind the dynamic response in the fully composite model. The FE analysis also revealed that “the number of shear stud connections affected the dynamic deflection, slip, and separation. The dynamic response of the FRP deck system was compared with that of the commonly used RC system” [227].

Research is ongoing to determine the temperature distribution and corresponding deflections in FRP decks, because “the current temperature design specifications in the AASHTO LRFD may no longer be valid for GFRP bridges” [233]. A long-term temperature monitoring project was designed to track the deflections of an FRP bridge deck responding to the local weather in Kansas [234]. Results showed that deck deflections were proportional to the difference in temperature between the upper and lower surfaces of the FRP panel and that deflections induced from the weather were on the same order of magnitude as traffic induced deflections and should be included in design procedures.

In 2013, research was conducted to determine if a more complex core assembly would improve the strength of an FRP-balsa wood composite deck [235]. “The best overall performance in terms of structural efficiency (stiffness and resistance) and weight resulted from a core configuration with a GFRP arch between an upper high-density and lower low-density balsa core” [235].

In 2014, a study was conducted to test FRP deck panels with polyurethane foam cores as a more cost effective alternative to FRP honeycomb sandwich panels [236]. The honeycomb structure is expensive to construct because it is so complex, but the PU foam would be much more cost effective and would lower first costs, making FRP decks more appealing to bridge owners as an option for rehabilitation or new construction. Test results led the research team to recommend PRISMA FOAM be used to make sandwich panels as an alternative deck system, although additional research is needed prior to field implementation including panel-to-girder connections, panel level connections, and accommodations for various road geometries (skew, roadway crown).

3.3.3.3 Research to increase the durability of bridge decks

Several articles were found on efforts to increase the durability of decks. These studies ranged from experimenting with corrosion resistant reinforcing bars to more resilient overlays and patching material.

Tennessee Department of Transportation experimented with Class L ternary (sand-lightweight ternary) mix for their bridge decks and found that it increased surface resistivity and decreased chloride ion penetration compared to the standard Class D (normal weight nonternary) bridge deck mix [237].

Iowa, Missouri, and Virginia reported using fiber-reinforced concrete (FRC) for the bridge decks of some of their IBRC projects. The fibers are expected to increase the toughness and strength of the concrete and resist and control cracking. Iowa designed a 'steel-free' bridge deck, with no reinforcement besides the composite fibers. This worked well in the main portion of the deck, but reinforcing bars were still needed in the deck overhang areas. The deck was a single span on steel girders and performed well under loading, with results within specification limits. Missouri used FRC in conjunction with FRP reinforcement for their bridge deck and reported that workability was not a problem. Virginia reported that their FRC deck had fewer, narrower cracks than conventional concrete decks even though it experienced more shrinkage, and that the fibers were particularly effective in controlling cracking over the piers. The residual strength of the deck is directly proportional to the fiber content. Also, the permeability of FRC is comparable to that of conventional concrete. The addition of synthetic fibers can increase the cost of concrete by 25 to 40%, but this increase in cost is expected to be offset by the increased service life.

Cracking in decks is a major concern, as cracks lead to exposure and deterioration of rebar. Methyl Methacrylate (MMA) Polymer Concrete materials have been successfully implemented for repairs in the field, "applied under a wide variety of conditions, temperatures and application/construction requirements" [238]. These MMA based materials set rapidly, heal, seal, and patch cracks and spalling, and protect the structure from future deterioration.

Self-consolidating concrete (SCC) was used to repair concrete defects on a bridge in the Shanxi province, where the defects were caused by high temperatures during the construction of the bridge [239]. The SCC used two types of sand with different moduli of fineness to produce excellent workability, the sand with lower modulus serving in place of a thickening agent. Quick and efficient construction is critical to maintain flowability of SCC, especially at high temperatures, and moist curing is important to obtain good quality, durable concrete.

Steel corrosion of reinforcing bars in decks is a huge maintenance expense. Canada constructed steel-free decks in an effort to eliminate this issue [240]. Wide cracks formed in the decks roughly midway between supporting girders, so GFRP bars, which do not corrode, were used in future deck constructions to serve as a crack control mesh and are referred to as ‘second generation steel-free deck slabs’ [216]. The first field implementation of the second-generation slab was on the Red River Bridge in Winnipeg, Canada. External steel straps were installed on the deck to obtain the highest static strength of the bridge deck. A structural health monitoring system was also installed on the deck for observation and data collection.

The experimental and analytical study of punching strength and failure mode of concrete deck slabs reinforced with GFRP bars is given in [241]. Test results showed that increasing the lateral restraint stiffness enhanced arching action which led to higher punching strength, lower GFRP reinforcement strain, and altered the failure mode from flexural punching failure to shear punching failure. The authors proposed a theoretical procedure based on an arching theory they developed to predict strengths. The results of this proposed theory are better than other analytical models in the literature. The authors also provide design recommendations for GFRP-reinforced concrete bridge deck slabs to avoid rupture of FRP bars.

In a 2014 study, research was published that proposed FRP bars could be used as reinforcement or prestressing strands for AASHTO I-girders, specifically Type 1, and would satisfy the strength and deflection criteria set by AASHTO [242]. However, those who choose to use FRP bars must bear in mind that the failure mode changes from concrete crushing to FRP tendon rupture in the bottom flange because not enough FRP tendons can be placed in the flange to prevent rupture prior to concrete crushing.

CFRP tendons were used to replace steel tendons in prestressed concrete bridge deck panels for an IBRC project in Colorado. The fatigue behavior of CFRP prestressed deck panels was investigated in laboratory experiments and test results showed that the panels prestressed with CFRP demonstrated the same performance as steel prestressed panels [243]. The test results also showed that the portion of the deck with precast panels "performed better than the full-depth cast-in-place segments due to the enhanced strength and crack resistance introduced by the prestressed panels" [243].

While not a strengthening technique, an alternate method to using FRP reinforcing to eliminate steel corrosion is to use MMFX bars which are made of a non-corrosive steel [244]. Several IBRC projects involved MMFX bars in bridge construction, and are listed in Table 9. Some IBRC projects also used galvanized, stainless steel, and stainless steel clad rebar. However, most projects used MMFX to reinforce bridge decks.

MMFX stands for Micro-composite, Multi-structural Formable steel, which means it is low-carbon, chromium bearing reinforcing steel. MMFX bars have nearly two times the yield point of standard steel rebar, so care must be taken not to design the deck to be over-reinforced. North Carolina proposes that 33% less reinforcement is needed when using MMFX bars in place of Grade 60 steel. Many of the projects were conducted to determine the long-term performance of MMFX bars under corrosive environments. The short-term performance of MMFX bars were reported to be very similar to standard steel. New Mexico reported that the initial installation of MMFX bars was successful and they have used the technology on bridges at higher elevations in more severe environments.

Table 9. IBRC Projects using MMFX reinforcing bars

Element Reinforced	**State**	**County**	**Project**
Deck	DE	New Castle	BR 119 on State Route 82 over Red Clay Creek
Girder	DE	New Castle	BR 712B, Ramp J, I95 Service Area, Newark
columns, footing	FL	Pinellas	Jensen Beach Causeway (MMFX)
Deck	IA	Grundy	US 20/South Beaver Creek Proj. NHSX-520-5(78)
deck and parapet	ID	Boise	State Route 21over Mores Creek at New York Gulch
Deck	ID	Bonner	Westmond Bridge, US 95 over BSFRR
Deck	KY	Scott	Rd. 5218 over North Elkhorn Creek
Deck	MI	Wayne	I-94 over Shook Road and C&O RR
substructure	MI		I-94EB & WB over Riverside Drive
Deck	NC	Johnston	State Route 1178 over I-95, Town of Four Oaks, TIP: I-2704, 2- span continuous steel structure (6 beam)
Deck	NM	Rio Arriba	US 64 over the Amargo River in Dulce, NM
lab testing	SC	Charleston	SC Route S-54 over Tidal Creek
Deck	TX	Potter	Washington Street Under IH-40
Deck	UT	Weber	East Bound State Route 79 Grade Separation/Reeves Rd.
Deck	VA		Route 123 at Occoquan River
Deck	VT	Orleans	VT Bridge 64, VT 105 over Clyde River

Note: Adapted from *Project case studies for IBRC and IBRD Programs*, by D. Paterson et al., 2012, FHWA unpublished internal document, p.711.

Idaho reports that the MMFX bars are much easier to handle and install than epoxy-coated rebar, because there is no protective coating to worry about damaging which would then require repair. This leads to faster installation times, especially since no repair is needed. Damage due to handling and transportation is also not an issue for MMFX bars.

One drawback of MMFX bars is that they are a proprietary product; therefore they are more expensive than standard steel. Also, due to the limited number of manufacturers, the availability of suppliers is limited, which can lead to construction delays. However, many of the IBRC projects initially planned to use stainless steel rebar because it performs better than MMFX bars, but stainless steel bars were completely unavailable, so MMFX bars took their place. South Carolina conducted laboratory tests and determined that stainless steel rebar provided the longest service life, followed by MMFX bars, and then carbon steel rebar. The cost of stainless steel is nearly double that of MMFX, so the recommendation is that stainless steel only be considered for applications where severe corrosion attack is possible.

The estimated service life of a deck reinforced with MMFX rebar is a minimum of 75 years without maintenance. The state of Michigan reported that the bond strength of MMFX rebar is comparable to uncoated bars, but lap length needs to be further studied, so the recommendation is to "reduce or eliminate lapped joints, either by mechanical splices, or requiring the contractor to supply the exact length reinforcing bars as detailed on the plan sheets" [3]. North Carolina reported that bonded bent bars perform similar to straight bars and can reach the same ultimate strength and strain as straight bars. The strength and strain capacities of unbonded bent MMFX bars decreases significantly past a strain of 1.5%, which is important to know if using MMFX as lifting hooks. MMFX bars were able to control deck cracking due to temperature and shrinkage on a Kentucky bridge and kept crack widths well below AASHTO limits. A bridge deck reinforced with MMFX bars in North Carolina had the same service deflection as a deck reinforced with Grade 60 steel. The ultimate capacity of the bridge deck was 10 times the strength specified by AASHTO.

3.4 Specifications and Guidelines

Specifications provide uniform standards to ensure certain strength is achieved in constructed and repaired members. Many authors have developed guidelines and procedures for design and analysis concerning composite materials to update the current design codes. These guidelines propose what materials can be used for certain applications, how much of the material should be used, and how it should be implemented. When new strengthening materials or methods are developed, destructive testing must be conducted to verify that the desired level of strength can be reached before field implementation can be accepted as safe and the desired strengthening effect is validated. The new guidelines are written based on the database of destructive laboratory testing. Following specifications assures that the structure will reach a certain level of strengthening before the composite will fail. Proposed design and analysis procedures are given in the following sections, for FRP decks, shear strengthening with FRPs, and flexural strengthening with FRPs. This chapter closes with a list of published guidelines and specifications from AASHTO, the American Concrete Institute (ACI), and National Cooperative Highway Research Program (NCHRP).

3.4.1 FRP Decks

A simplified FRP deck design and analysis procedure was developed by Davalos and Salim, based on “a first-order shear deformation macro-flexibility (SDMF) orthotropic plate solution” [245]. A conceptual design for rapid replacement of short-span rural bridges with cellular FRP deck sections, allows designers “to analyze and optimize various case studies before implementation in the field.”

Chen and Davalos developed design equations for an FRP Deck Steel Girder Bridge System [246]. They provide a design example in their paper. The guideline developed considers “the strength of the FRP deck subjected to out-of-plane compression, out-of-plane shear, and bending; static and fatigue strengths of the deck-to-girder shear connector; and effective flange width of the bridge system” [246]. A book has also been published by Davalos, Chen and Qiao on analysis and design procedures for FRP decks on steel girders [247]. The book also covers topics of stiffness evaluation, strength evaluation, and mechanical shear connectors.

A parametric study of relative deck deflection and load distribution factors for FRP decks on steel girders was conducted to develop updates for the AASHTO code [248]. It was determined that the AASHTO LRFD strip method is appropriate, but different strip width equations must be derived for different types of FRP decks. The AASHTO LDF equations for glulam decks on steel girders and the lever rule are also appropriate to use on FRP decks on steel girders.

An analysis and design technique for FRP web core decks for highway culverts is proposed in [249]. This technique uses FE modeling and iterative optimization for different span lengths, using deflection limit, global buckling and different failure models as the parameters.

3.4.2 Shear Strengthening with FRPs

While research is still ongoing to understand the behavior of structures strengthened in shear with FRP materials, design guidelines were proposed in 2011 by [250], and in 2012, AASHTO published “Guide Specifications for Design of Bonded

FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 1st Edition" [251]. Figures 13 and 14 show various strengthening schemes for shear strengthening of concrete beams.

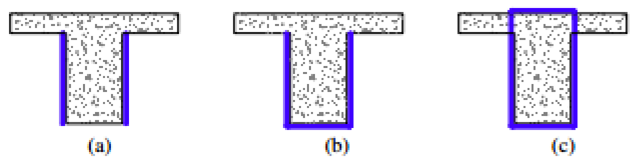


Figure 13. Strengthening Scheme: Cross-Sectional View. (a) Side bonding, (b) U-wrap, and (c) Complete wrap. *Figure B3.1.* Strengthening Scheme: Cross-Sectional View. Reprinted from *Design for FRP systems for strengthening concrete girders in shear*, by A. Belarbi et al., 2011, *NCHRP 678*, p.61. Copyright [2011] by National Academy of Sciences.

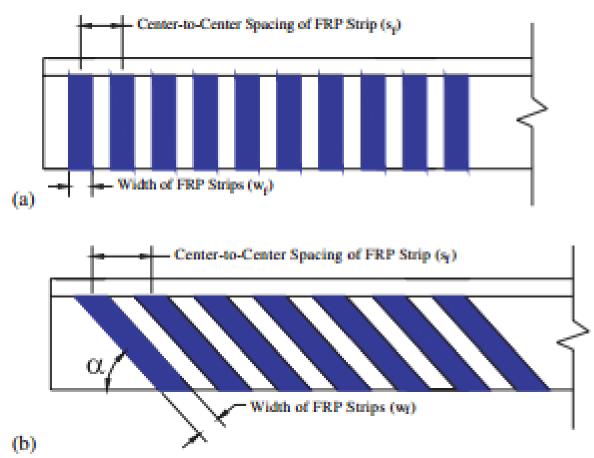


Figure 14. Strengthening Scheme: Side View – (a) Fibers at 90° direction, and (b) Fibers at Inclined Direction. *Figure B3.2.* Strengthening Scheme: Side View. Reprinted from *Design for FRP systems for strengthening concrete girders in shear*, by A. Belarbi et al., 2011, *NCHRP 678*, p.62. Copyright [2011] by National Academy of Sciences.

The reliability of concrete bridge girders strengthened with FRP in shear was investigated in [252]. The study showed that approximate expressions for reliability index calculations were unacceptable due to the high scatter of results in the experimental data. The paper used Monte Carlo simulations and first-order reliability method (FORM) to analyze the developed limit state function. Results show that the reliability indices calculated by the new design expressions fall within the 3.00-3.50 target range of most codes, but fall below the 'greater than 3.50' target value of AASHTO LRFD in some cases [252].

A 2012 study was conducted on concrete T-beams strengthened in shear with CFRP sheets and reported "A comparison of predicted values with experimental results indicates that the (ACI 440.2R-08, UK Concrete Society TR55, and fib Bulletin 14) guidelines can overestimate the shear contribution of the externally bonded FRP system" [253].

3.4.3 Flexural Strengthening with FRPs

The University of Mexico conducted a project to develop guidelines for the design and implementation of FRP strengthening systems on concrete bridges [254]. As national guidelines become available, individual states are modifying the codes for their specific geography and climates. Wayne State University and the Michigan DOT collaborated on a project to develop *Design and construction guidelines for strengthening bridges using fiber reinforced polymers (FRP)* [255], specifically for bridges in Michigan which are subject to a wide range of temperature and moisture changes. Separate design, construction, maintenance, and inspection guidelines specifically for FRP are needed because the complex environmental and mechanical loading effect on the durability of FRP is different than on traditional materials.

International exchange of knowledge is valuable in the evolution of guidelines and specifications. Ingram reports that Australia used ACI440.2R guidelines in a national project upgrading many roads with FRP [256]. Although the specification was applicable, it did not 'seamlessly fit into the design framework of AS5100.5' [256]. Efforts were made to modify the American specifications to include in the Australian code.

A guideline for the design of high modulus CFRP materials for the strengthening of steel girders is given in reference [257]. "The flexural design procedure is based on a moment-curvature analysis and a specified increase of the live load carried by the bridge to satisfy specific serviceability requirements" [257]. The paper proposes installation techniques to prevent debonding and "A bond model is also described which can be used to calculate the shear and peel stresses within the adhesive thickness". Finally, the paper presents a worked design example. The conclusion given is that high modulus CFRP materials can successfully increase the strength and stiffness of steel girders.

The strut-and-tie method is proposed as an appropriate analysis method for deep concrete beams strengthened with FRP composites [258]. Results from 17 experimental deep beam tests show that the "STM approach with an effective factor model depending on the strut angle provides the best agreement with the test results" [258]. The paper also presents a design process for CFRP strengthened deep RC members.

Since NSM FRP has become an accepted method of bridge strengthening, the American Concrete Institute (ACI) guideline assigns an additional partial strength reduction factor to the contribution of the FRP repair. This conservative method accounts for the higher variability of FRP due to the material and the installation. One study set out to define a more accurate single strength reduction factor for the design of

NSM FRP repairs [259]. Statistical data is computed with a computerized Monte Carlo simulation technique and is used "to recommend revised strength reduction factors for flexural RC members strengthened with NSM FRP bars that eliminate the partial factor, and yet, provide a safety level equal to ordinary steel RC members" [259].

3.4.4 List of Guidelines and Specifications

Below is a list of AASHTO, American Concrete Institute (ACI), and National Cooperative Highway Research Program (NCHRP) guidelines and specifications related to strengthening structures with FRP materials. These documents should be consulted when retrofitting bridges with composite materials.

- AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, First Edition (2009).

- AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 1st Edition (2012).

- ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (2008).

- ACI 440.7R-10 Guide for Design & Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures (2010).

- ACI 440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing of Strengthening Concrete Structures (2012).

- ACI 549.4R-13 Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures (2013).

- ACI 440.8-13 Specification for Carbon and Glass Fiber-Reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures (2014).

- NCHRP Report 564: Field Inspection of In-Service FRP Bridge Decks (2006).

- NCHRP - Report Document 155: Design Guidelines for Durability of Bonded CFRP Repair/Strengthening of Concrete Beams (2008).

- NCHRP Report 609: Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites (2008).

- NCHRP Report 655: Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements (2010).

- NCHRP Report 678: Design of FRP Systems for Strengthening Concrete Girders in Shear (2011).

Chapter 4

FRAMEWORK FOR BRIDGE REHABILITATION WEBSITE

4.1 Background and Set-Up

Technology is advancing at a rapid pace and bridge strengthening methods are evolving accordingly. A website that gathers new information in one place and makes it accessible to bridge owners and engineers would be very valuable. This is the motive behind the creation of a website framework. The goal is to develop a living website that is continually updated with information and case studies on new technologies, where the bridge community can stay connected and up-to-date on state of the art strengthening methods. The website would provide an efficient means of gathering and distributing new information, and would be an alternative to creating time consuming synthesis reports every decade or two, as has been done in the past. The potential this website presents for wide-spread availability of information about new strengthening methods could significantly influence how repairs are performed in the field, simply because bridge owners and engineers may more easily educate themselves on their options.

Other web-based decision guides were researched and used as models for the framework of the bridge rehabilitation website. The bridge rehabilitation website prototype can be accessed thru www.sites.udel.edu/coe-bridge/. Each page of the website framework is adapted from www.geotechtools.org [260],with the exception of the Case Studies page, which is adapted from www.itrcweb.org/miningwaste-guidance/case_studies.htm [261], as noted. The color scheme is borrowed from www.fhwa.dot.gov.

Screen shots of each page of the website framework are shown and discussed in the rest of this chapter. Regular text is shown in black, while clickable text, which will lead the user to another page, is underlined and shown in blue, with the exception of the navigation bar. Downward triangles indicate a drop-down menu. A side arrow shows where the user should click to navigate to the next page.

Figure 15 shows a flow chart of the website. Each branch of the website can be accessed from the *Home* page. Two branches of the website, *Catalog of Technologies* and *Technology Selection*, both take the user to the individual *Technology Information* pages, which will be discussed later. This flow chart will serve as a visual reference for the remainder of the chapter. The headings of the following chapter sections correspond to the *Home* page and four main branches of the website shown in the flow chart: *Catalog of Technologies*, *Technology Selection*, *Resources*, and *Contribute*. This chapter will discuss each section and its corresponding subsections in the order previously listed.

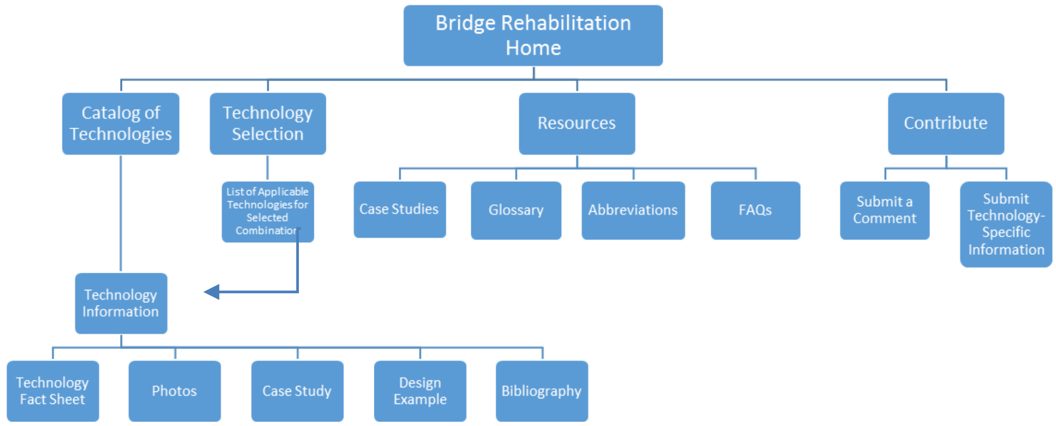


Figure 15. Bridge Rehabilitation Website Flow Chart

4.2 Home Page

The *Home* page, shown in Figure 16, consists of many components. The heading includes the title of the site, “Bridge Strengthening and Repair Methods,” and the Center for Innovative Bridge Engineering logo, and is constant on every page of the website. The footer is also constant through every page of the website and lists the project title that is responsible for the framework development. The navigation bar is located beneath the heading and lists the major categories of the website: *Home*, *Catalog of Technologies*, *Technology Selection*, *Resources*, and *Contribute*. The actual page portion of the home page lists three categories, which represent the main branches of the website: the *Catalog of Technologies*, *Technology Selection*, and *Contribute.* Descriptions of the different branches are listed under the titles and will be discussed later in the chapter. The first and second category headings also act as links to their respective pages, which is why they are underlined and shown in blue. Clicking ‘*Home’* on the navigation bar from any page on the website will bring you back to this page. The navigation bar can also be used to access the other main pages of the website, as shown in Figure 17.

4.3 Catalog of Technologies

By clicking on the '*Catalog of Technologies*' heading in the navigation bar, or on the home page, you are taken to the *Catalog of Technologies* page of the website, shown in Figure 18. The *Catalog of Technologies* page corresponds to the first branch of the flow chart shown in Figure 15. The *Catalog of Technologies* page provides an alphabetical, comprehensive list of the bridge strengthening and repair methods for which information is available on the website. The list includes technologies that are recognized as traditional bridge strengthening methods and also innovative bridge strengthening methods and technologies that have been developed in the last 20 years. The underlined technologies, shown in blue, will take the user to the *Technology Information* page about that technology, where they can access information in PDF format. The technologies shown in black with downward triangles have drop-down menus of multiple technologies that are categorized together. These drop-down menus are shown in Figure 19.

The user can click on underlined blue text in the catalog list or in the drop-down menus to navigate to a specific *Technology Information* page, as shown in Figure 20.

Figure 21 shows that each *Technology Information* page offers the user a brief general description, a photo or diagram, and several PDFs on the selected technology. The list of PDFs includes *Technology Fact Sheets, Photos, Case Studies,* a *Design Example*, and a *Bibliography*. On the right side of the page is a list of all the technologies for easy navigation between *Technology Information* pages. To access the PDFs, the user must click on the underlined blue text, as shown in Figure 22.

The *Technology Fact Sheet PDF*, shown in Figure 23, provides basic information about the technology to the user. The information is grouped into the following categories:

- Basic Function
- Advantages
- General Description
- Structural Applicability
- Construction Methods
- Additional Information
- Example Successful Applications
- Complementary Technologies
- Alternate Technologies
- Potential Disadvantages
- Key References for this Fact Sheet.

The *Photos PDF*, shown in Figure 24, provides a collection of diagrams and photographs of the selected technology. The diagrams can represent design drawings of the strengthening technology, while photographs are useful to show how the technology is applied and what the final product looks like in the field.

A *Case Study PDF* offers information on a successful bridge strengthening project which used the selected technology. Figure 25 shows a case study of the Trout Brook Bridge, which was strengthened with a GFRP fabric U-wrap. The case study provides pictures of the project as well as other useful information such as the location, owner, and year constructed. The project scope is given along with complementary technologies used, project cost, and any references to papers published on the project.

A *Design Example PDF* offers the user a step-by-step process for designing the selected technology. Figure 26 shows the introduction and summary pages of a design example of flexural strengthening of a simply supported cast-in-place girder with FRP strips. The rest of the PDF also includes references to commonly used specifications for the selected technology, a list of symbols and notations used in the design example, and of course, the detailed step-by-step solution for the design example. The design procedure is summarized as follows:

1. Calculate nominal bridge capacity/resistance
2. Calculate desired bridge capacity
3. Design strengthening system
4. Check design against limits and requirements

The Bibliography PDF, shown in Figure 27, collects all the references available on the website of a selected technology in one document. These references are used to fill out the other PDF documents. At the end of the bibliography is a reference matrix, shown in Figure 28. The reference matrix identifies the topics addressed in each application for easy user navigation. The topics listed at the top of the matrix are consistent throughout the bibliographies for each technology, so only a subset of technology topics will be covered by any referenced application. This explains why some topics shown in Figure 28 are not represented.

4.4 Technology Selection

The navigation bar can be used to access the *Technology Selection* page, as shown in Figure 29. *Technology Selection* is the second branch of the flow chart in Figure 15.

The *Technology Selection* page offers a matrix of member strengthening methods and a list of structural modification strengthening methods, to help the user determine which methods are applicable for their specific project. The matrix of member strengthening methods is organized by classification and structure type, as shown in Figure 30. The classifications are flexural strengthening, shear strengthening, and deck strengthening, while the structure types are concrete, steel, and timber. The user may select any combination within the table to access a list of applicable technologies. The list of applicable technologies given only includes the methods which strengthen existing bridge members, which is why the list of ‘structural modification strengthening methods’ is also listed on the *Technology Selection* page. The list of structural modification strengthening methods involves technologies which require altering or replacing parts of the bridge to achieve an increase in capacity, rather than strengthening existing members. These methods include lightweight deck replacement, developing additional continuity, and providing composite action.

The user may select any of the underlined blue text under ‘Structural Modification Strengthening Methods’ to access a *Technology Information* page. The user may also select any combination in the matrix of ‘Member Strengthening Methods’ to access a list of applicable technologies, as previously stated. This matrix selection is shown in Figure 31, and a corresponding path is shown in the flow chart of Figure 15.

The list of applicable technologies given for the selected combination of member strengthening provides the user with individual technologies that may be applied to their project, shown in Figure 32. Selecting any of the technologies listed will take the user to the appropriate *Technology Information* page, as represented in the flow chart of Figure 15. A *Technology Information* page was shown in Figure 21.

4.5 Resources

The *Resources* tab on the navigation bar opens a drop-down menu for the user as shown in Figure 33. The resources listed are *Case Studies*, *Glossary, Abbreviations*, and *FAQs*. Selecting one of the resources will take the user to the corresponding page. These resource pages are listed in the third branch of the flow chart in Figure 15.

The *Case Studies* page, shown in Figure 34, is adapted from http://www.itrcweb.org/miningwaste-guidance/case_studies.htm. This page offers a complete collection of the case studies included on the site, providing easy access for the user. The page includes an interactive U.S. map showing the locations of the case studies listed in the table below the map. The user may click on a state on the map, which will guide the user to the list of case studies in the table under that state. The 'Case Study Table' is organized alphabetically by state. Each case study entry includes the name of the case study project, the technology used, and the corresponding number on the map. The case studies listed in the table will lead the user to a PDF of the case study when selected.

The *Glossary* page, shown in Figure 35, offers definitions of terms that may be unfamiliar to the user, especially terms which relate to innovative bridge strengthening methods. The glossary is organized alphabetically.

The *Abbreviations* page, shown in Figure 36, offers explanations of acronyms used throughout the site that the user may be unfamiliar with, especially those that relate to innovative bridge strengthening methods. The abbreviations are organized alphabetically.

The *Frequently Asked Questions* page, shown in Figure 37, offers a list of FAQs and their corresponding answers. Each question is included in a succinct list at the top of the page and can be clicked on to direct the user to the answer located further down the page. The questions cover topics about the formation of the website and how to submit supplemental information.

4.6 Contribute

The *Contribute* tab of the navigation bar also opens a drop-down menu for the user as shown in Figure 38. The user can select one of two ways to contribute: *Submit Technology-Specific Information*, or *Submit a Comment*. These contribution options are shown in the fourth branch of the flow chart in Figure 15.

The *Submit Technology-Specific Information* page encourages users (primarily governmental agencies) to contribute to the website, to keep the information up-to-date with methods being applied in the field. As users take advantage of this feature, the site will become increasingly more valuable. To submit technology-specific information, the user must fill in the required fields on the page shown in Figure 39. The required information includes contact information, the topic the submission falls under, and why the submission should be added to the site. The user can upload a file on this page. The file can be a case study, photograph, or a reference. To make the incorporation of newly submitted information as streamline as possible, there is a case study template that the submission must follow in order to be considered. A link to download the template is listed at the top of the page, along with a link to a Word document of guidelines that direct the user in how to fill out the template or submit other files properly. The hosting agency of the website will review the submitted files to verify the material's relevance and value to the site.

Figure 40 shows the blank case study template. An example of the case study template filled out was shown previously in Figure 25. The blank template includes more sections than the filled out case study. This is because the user may delete categories for which they do not have the information, as long as the category is not required for submission, as specified by the guidelines.

The *Submit a Comment* page, shown in Figure 41, allows the user to submit comments about the website and updates or corrections for specific technologies. Contact information is required to submit a comment. A list of frequently asked questions is located at the top of the page to allow the user to find answers to questions they may have without having to submit a comment. There is also a link to the *Submit Technology-Specific Information* page in case the user wants to submit that type of information.

4.7 Website Pages

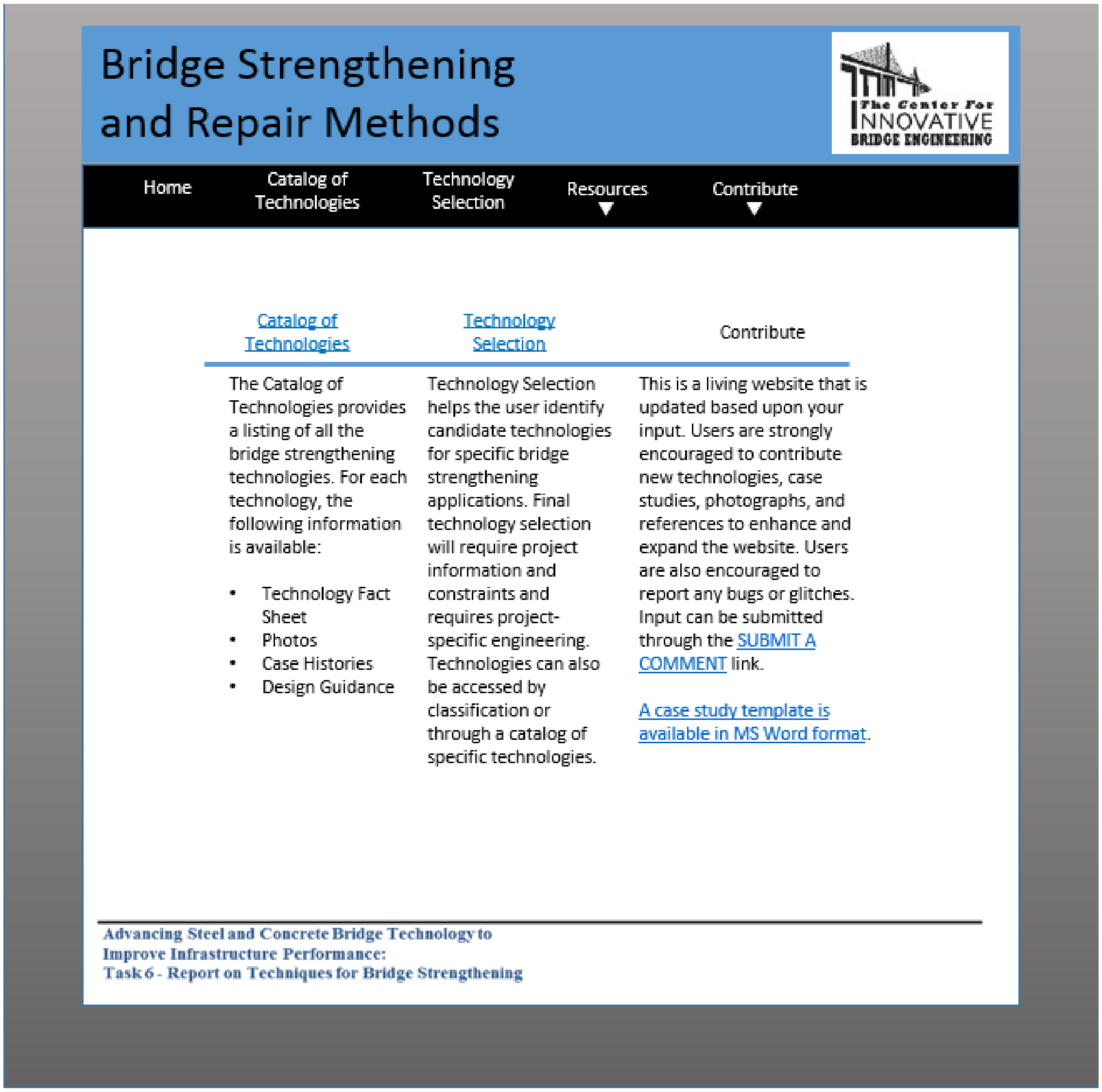


Figure 16. Website Home Page. [260]

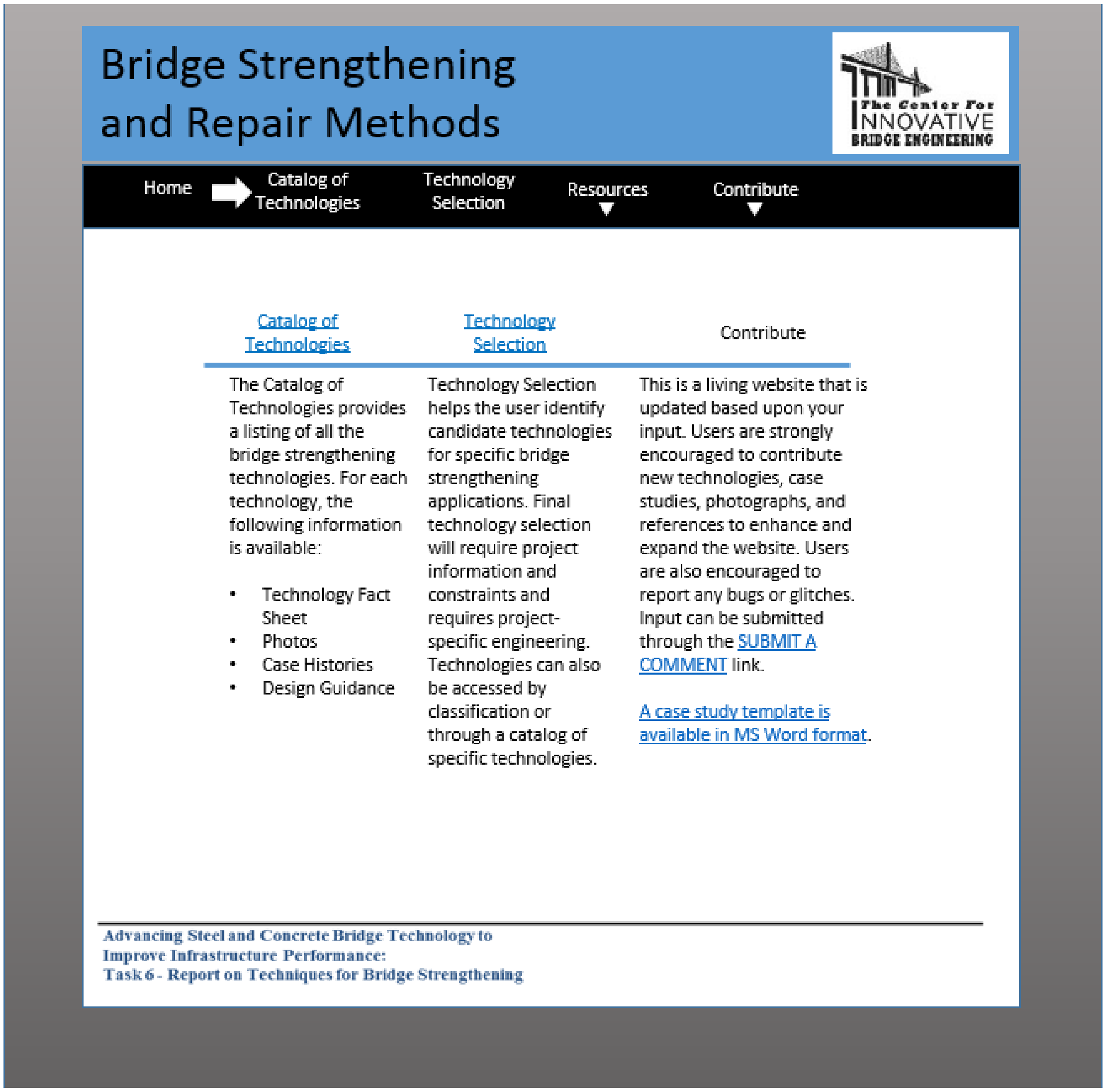


Figure 17. Home Page: Catalog of Technologies Tab in Navigation Bar. [260]

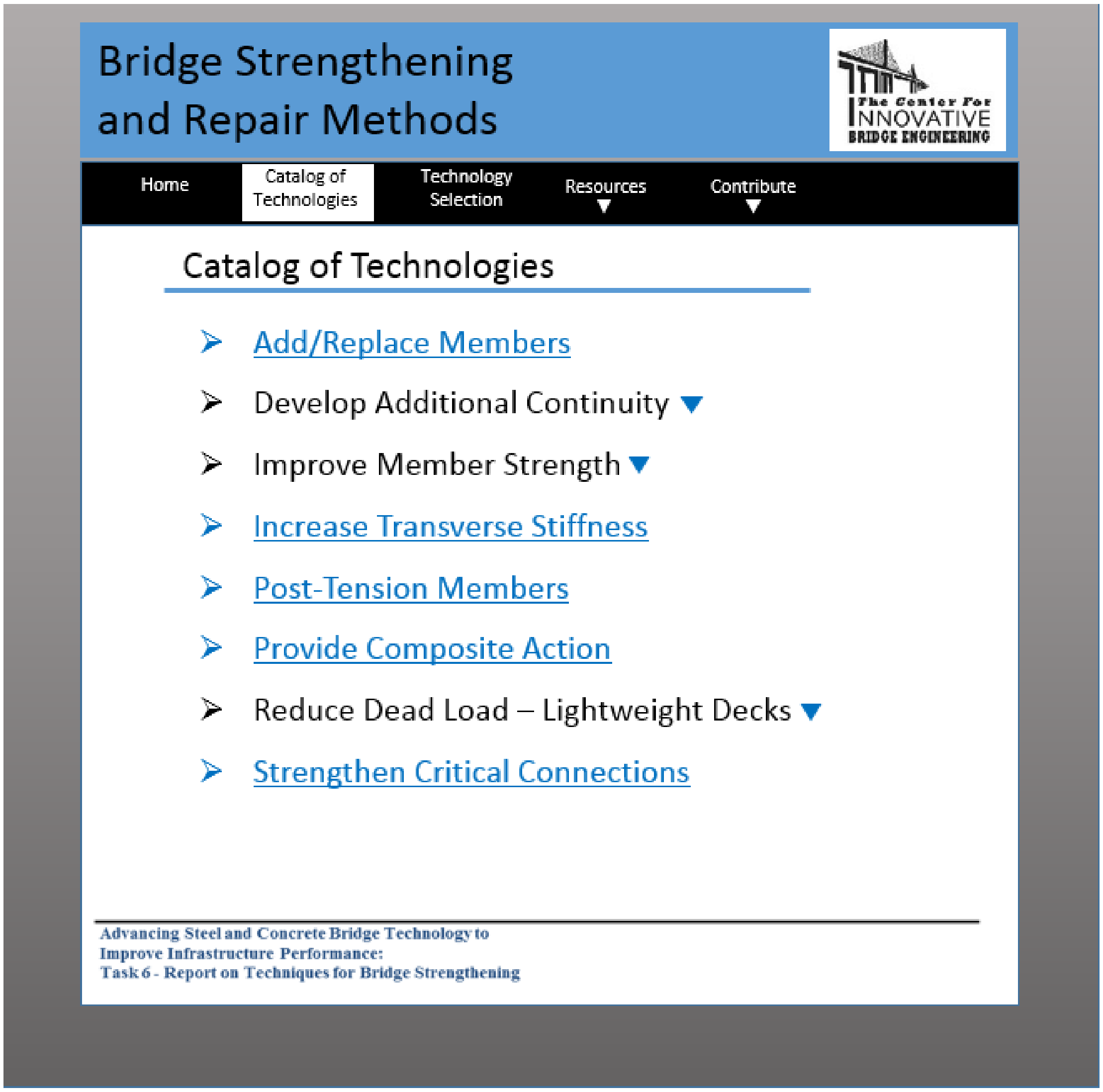


Figure 18. Catalog of Technologies Main Page.

Figure 19. Catalog of Technologies Drop-down Menus.

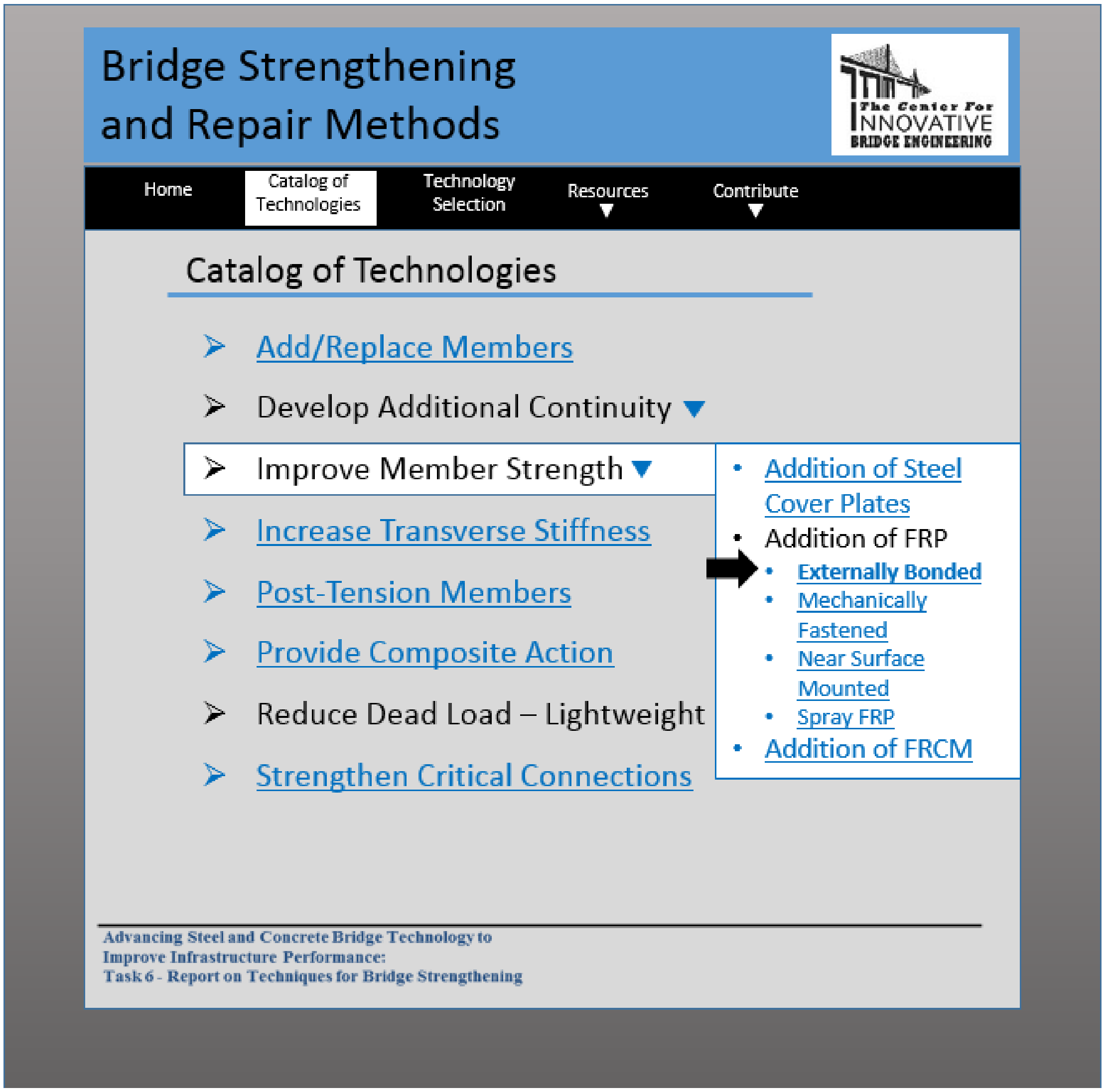


Figure 20. Catalog of Technologies: Select a Technology.

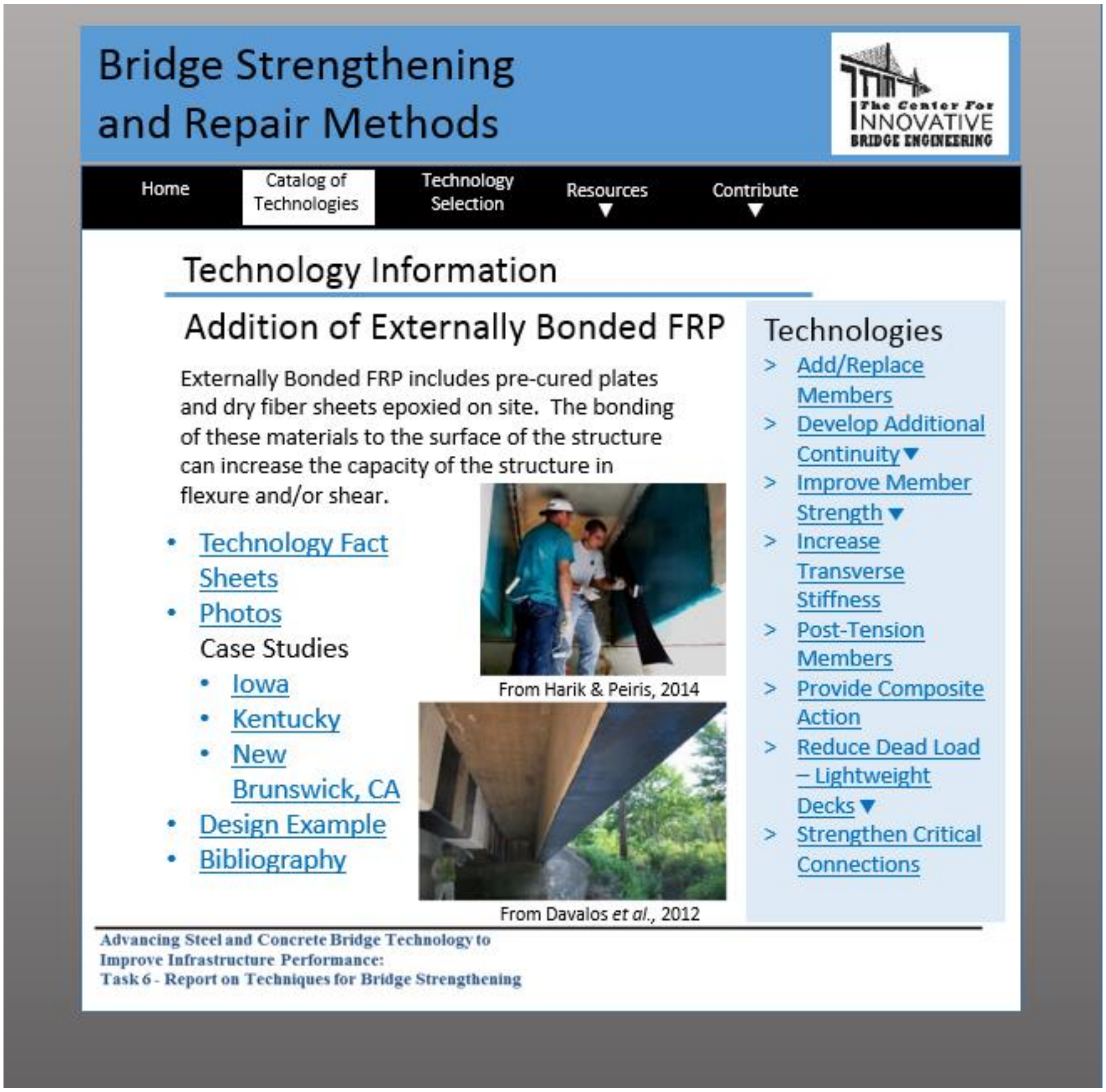


Figure 21. Catalog of Technologies: Technology Information Page. [262, 263]

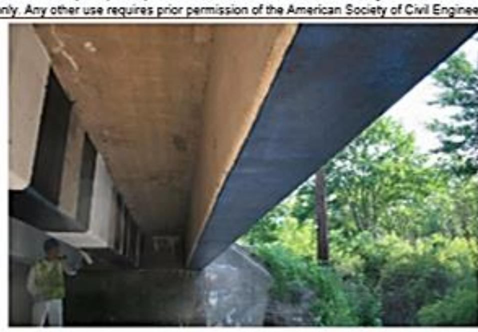
Figure 22. Catalog of Technologies: PDF Selection. [262, 263]

Technology Fact Sheet

APPLICATION OF FRP: EXTERNAL BONDING

August 2015 http://www.BridgeRehabMethods.org

FRP Strip Installation.
(Figure from Davalos *et al.* (2012) With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers)



Basic Function

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy to increase the structure's capacity in flexure and/or shear.

Advantages:

- Rapid installation: Curing time is a few hours
- Minimal Traffic closure, possibly not needed
- Increase in capacity with relatively little material
- No heavy lifting equipment required
- Can be applied by as few as two people
- Controls crack opening and propagation: improves member stiffness.

General Description:

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy. 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 to the structure when it cures.

Structural Applicability:

- Most commonly applied to concrete beams, but can also be bonded to steel girders, timber beams, truss structures, piers, columns, and the underside of decks.

Construction Methods:

First, the surface of the structure has to be prepared. The surface must be cleaned and roughened to ensure a good bond. Sometimes a priming agent may be applied to create a stronger bond. If using pre-cured plates, an adhesive layer of epoxy is applied to the structure's prepared surface, and the plates are put in place over the epoxy. Clamps are commonly used to hold the plates in place while the epoxy cures.

Dry fiber sheets can be used to accommodate varying structural surfaces, such as camber or wrapping around a bulb-tee beam. A layer of epoxy is applied to the structure, the fabric is smoothed over the epoxy and another layer of epoxy is applied over the fabric to saturate the fibers and create a continuous composite material.

Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance:
Task 6 - Report on Techniques for Bridge Strengthening

Additional Information:

Most external bonding is currently done by hand using the wet-layup technique. Vacuum-assisted resin transfer molding is an alternative way to apply externally bonded FRP. This requires machinery, but produces a higher quality composite that is stronger and more durable.

Example Successful Applications:

- Trout Brook Bridge– New Brunswick, Canada
- I-A-92 over Walnut Creek– Iowa
- KY 714 over Jeptha Creek– Kentucky
- Steel Girder Bridge– Kentucky

Complementary Technologies:

Externally bonded FRPs are often anchored with Mechanical Fasteners to prevent or delay delamination. Externally bonded FRPs can also be prestressed to maximize the increase in capacity gained from the retrofit.

Alternate Technologies:

Mechanical fasters can be used alone instead of in conjunction with external bonding. Near Surface Mounting is an alternate strengthening technique. Post-tensioning bars can also be used as an alternative.

Potential Disadvantages:

- Potential peeling or delamination of material
- More expensive than traditional repair materials
- Material has a proprietary nature, but specifications have been published to minimize the variability of retrofits.

Key References for this Fact Sheet:

Bologna, G., & Khabra, J. (2012). *Load rating upgrade of Trout Brook Bridge utilizing fiber reinforced polymer (FRP) composites*. Poster presented at the 2012 Conference and Exhibition of the Transportation Association of Canada – Transportation: Innovations and Opportunities, Fredericton, New Brunswick, Canada.

Davalos, J.F., Chen, A., Ray, I., Justice, A., & Anderson, M. (2010). *District 3-0 investigation of fiber wrap technology bridge repair and rehabilitation - phase III*.

Davalos, J., Chen, A., Ray, I., & Levan, J. (2012). Comprehensive study on using externally bonded FRP composites for the rehabilitation of reinforced concrete T-beam bridges. *Journal of Infrastructure Systems*, 18(2), 89-102.

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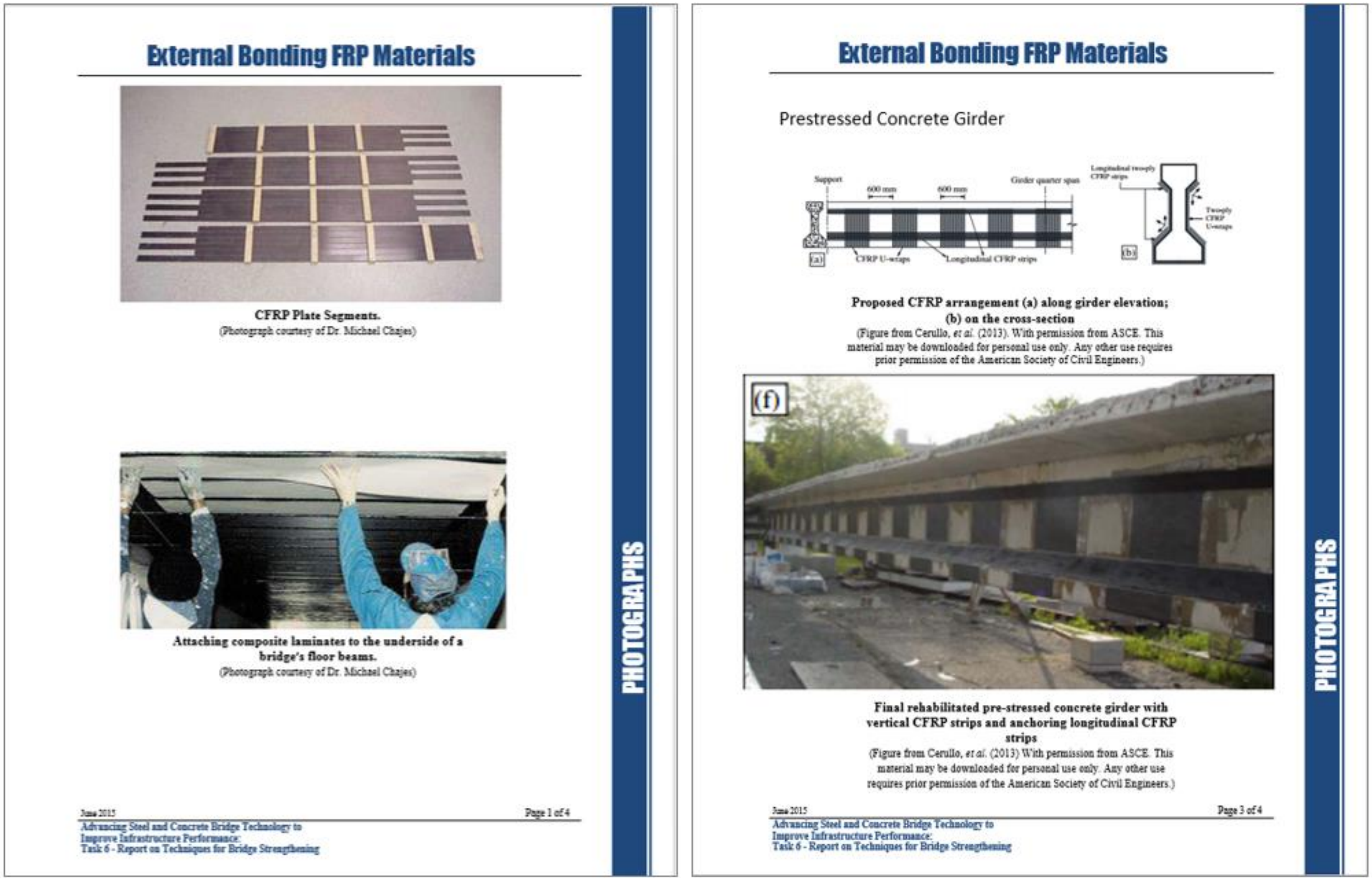
Figure 23. Technology Information PDFs: Technology Fact Sheet. [263]



External Bonding FRP Materials

CFRP Plate Segments.
(Photograph courtesy of Dr. Michael Chajes)

Attaching composite laminates to the underside of a bridge's floor beams.
(Photograph courtesy of Dr. Michael Chajes)

PHOTOGRAPHS

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External Bonding FRP Materials

Prestressed Concrete Girder

Proposed CFRP arrangement (a) along girder elevation; (b) on the cross-section
(Figure from Cerullo, *et al.* (2013). With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.)

Final rehabilitated pre-stressed concrete girder with vertical CFRP strips and anchoring longitudinal CFRP strips
(Figure from Cerullo, *et al.* (2013) With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.)

PHOTOGRAPHS

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Figure 24. Technology Information PDFs: Photos. [264, 265]

GFRP Fabric U-Wrap
Trout Brook Bridge
– Project Case Study –

Location: Victoria County, New Brunswick, CA, Route 109

Owner:
New Brunswick Department of Transportation and Infrastructure

Contractor:

Engineer:

Year Constructed: 2011

Project Photo or Drawing

Trout Brook Bridge finished repair (Photograph from Bologna & Khabra (2012))

Project Summary/Scope:
The objective of the Trout Brook Bridge retrofit was to provide additional shear capacity to the critical shear zones of all four girders at both ends. New Brunswick Department of Transportation required an increased load rating on their bridge to allow for the transport of heavier vehicular loading. Through analysis the Department of Transportation determined that in order to increase the bridge's load carrying capacity from 43,500 kilograms to 50,000 kilograms, each girder would have to be strengthened by a minimum of 120 kN. Each beam was strengthened to provide an increase in 120 kN for a specified length of 5 meters at each end. An effective and durable glass composite FRP was selected, with a single ply applied at each location to achieve the desired strength requirement. The FRP wrap was applied transverse to the longitudinal axis of the beams, effectively creating a "U-Wrap."
Prior to FRP application, however, all cracking issues had to be repaired.
Note: All composite materials were designed per CSA S6-06 standards.

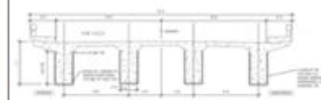
Complementary Technologies Used: Mechanical grinders used for surface preparation. Epoxy crack injection used to repair girders prior to FRP bonding.

PROJECT CASE STUDY

Additional Photo:

Trout Brook Bridge girders (Photograph from Bologna & Khabra (2012))

Additional Photo or Drawing:



Trout Brook Bridge AutoCAD detail. (Photograph from Bologna & Khabra (2012))

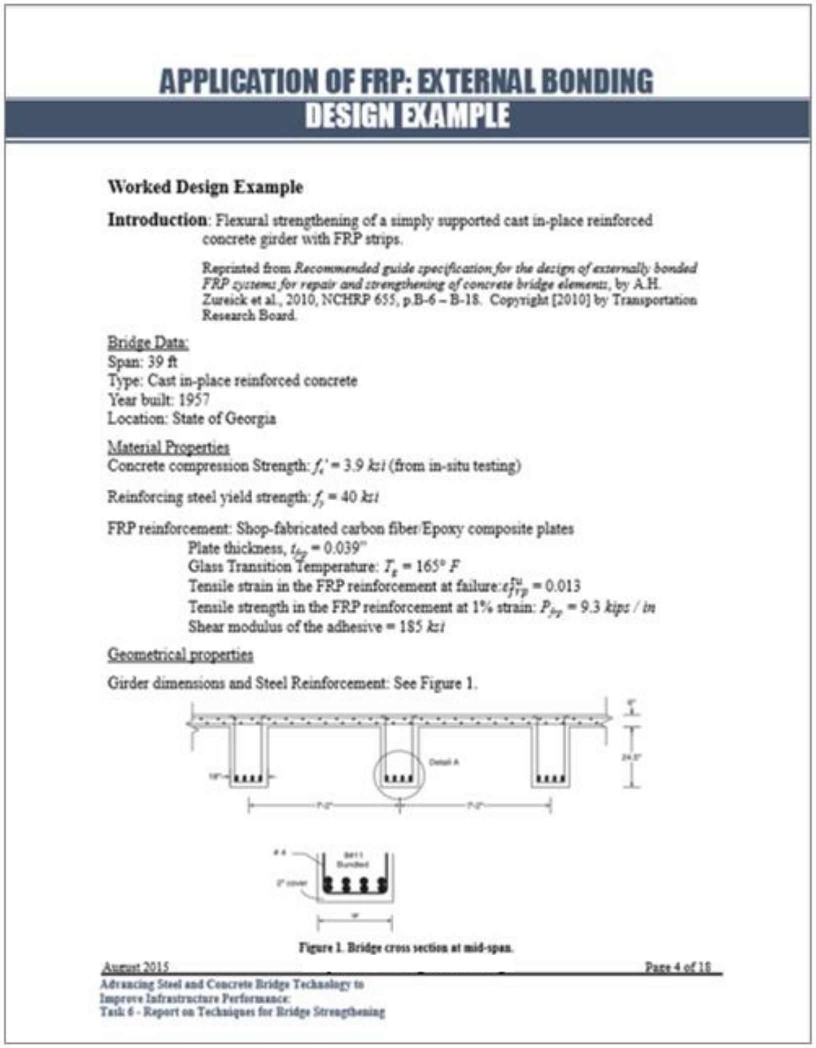
Cost Information: Total project cost was approximately $80, 000.

Case Study Author/Submitter: Gaetano Bologna and Jeewan Khabra

Project Technical Paper: Bologna, G., & Khabra, J. (2012). *Load rating upgrade of Trout Brook Bridge utilizing fiber reinforced polymer (FRP) composites.* Poster presented at the 2012 Conference and Exhibition of the Transportation Association of Canada – Transportation: Innovations and Opportunities, Fredericton, New Brunswick, Canada.

Date Case Study Prepared: 8/10/2015

Figure 25. Technology Information PDFs: Case Study. [266]



APPLICATION OF FRP: EXTERNAL BONDING
DESIGN EXAMPLE

Worked Design Example

Introduction: Flexural strengthening of a simply supported cast in-place reinforced concrete girder with FRP strips.

Reprinted from *Recommended guide specification for the design of externally bonded FRP systems for repair and strengthening of concrete bridge elements*, by A.H. Zureick et al., 2010, NCHRP 655, p.B-6 – B-18. Copyright [2010] by Transportation Research Board.

Bridge Data:
Span: 39 ft
Type: Cast in-place reinforced concrete
Year built: 1957
Location: State of Georgia

Material Properties
Concrete compression Strength: $f_c' = 3.9\ ksi$ (from in-situ testing)

Reinforcing steel yield strength: $f_y = 40\ ksi$

FRP reinforcement: Shop-fabricated carbon fiber/Epoxy composite plates
Plate thickness, $t_{frp} = 0.039"$
Glass Transition Temperature: $T_g = 165°\ F$
Tensile strain in the FRP reinforcement at failure: $\varepsilon_{frp}^{fu} = 0.013$
Tensile strength in the FRP reinforcement at 1% strain: $P_{frp} = 9.3\ kips / in$
Shear modulus of the adhesive = 185 ksi

Geometrical properties

Girder dimensions and Steel Reinforcement: See Figure 1.

Figure 1. Bridge cross section at mid-span.

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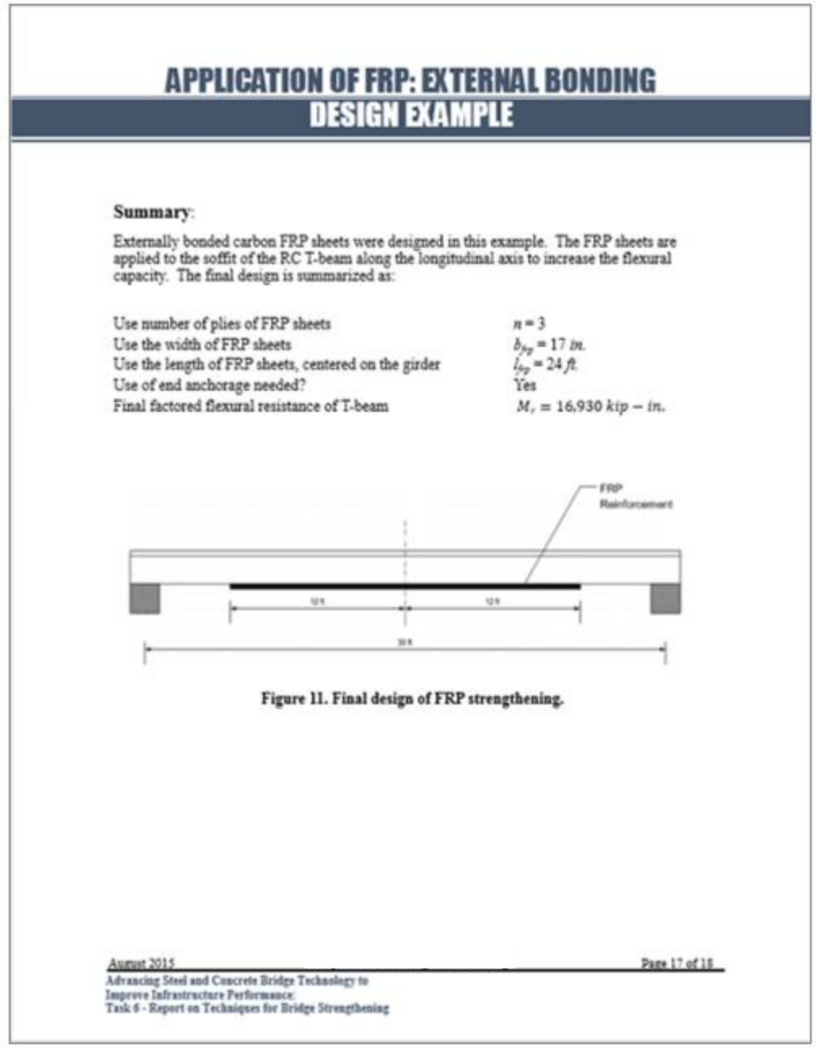

APPLICATION OF FRP: EXTERNAL BONDING
DESIGN EXAMPLE

Summary:

Externally bonded carbon FRP sheets were designed in this example. The FRP sheets are applied to the soffit of the RC T-beam along the longitudinal axis to increase the flexural capacity. The final design is summarized as:

Use number of plies of FRP sheets	$n = 3$
Use the width of FRP sheets	$b_{frp} = 17\ in.$
Use the length of FRP sheets, centered on the girder	$l_{frp} = 24\ ft.$
Use of end anchorage needed?	Yes
Final factored flexural resistance of T-beam	$M_r = 16{,}930\ kip - in.$

Figure 11. Final design of FRP strengthening.

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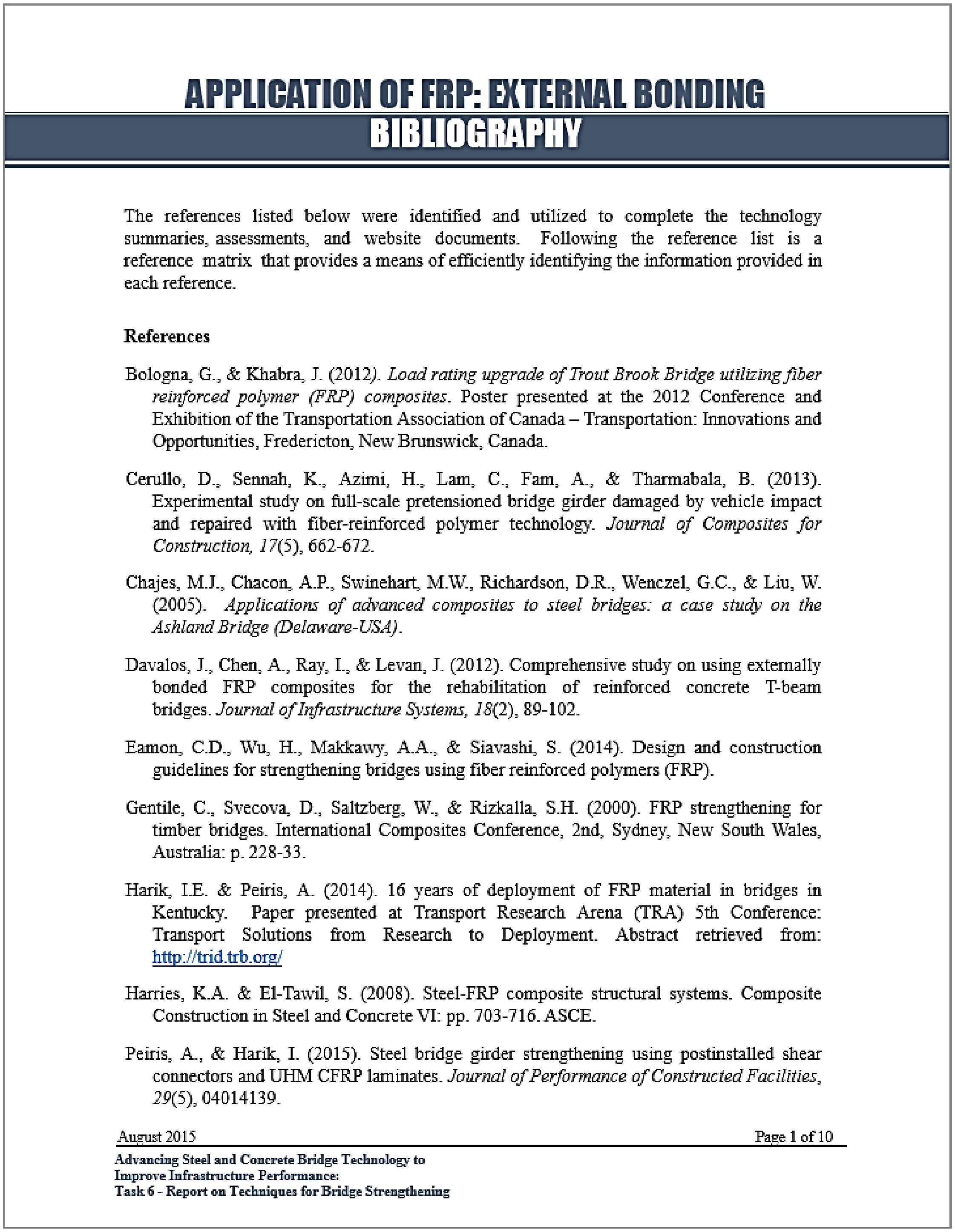
Figure 26. Technology Information PDFs: Design Example. [267]



APPLICATION OF FRP: EXTERNAL BONDING

BIBLIOGRAPHY

The references listed below were identified and utilized to complete the technology summaries, assessments, and website documents. Following the reference list is a reference matrix that provides a means of efficiently identifying the information provided in each reference.

References

Bologna, G., & Khabra, J. (2012*). Load rating upgrade of Trout Brook Bridge utilizing fiber reinforced polymer (FRP) composites*. Poster presented at the 2012 Conference and Exhibition of the Transportation Association of Canada – Transportation: Innovations and Opportunities, Fredericton, New Brunswick, Canada.

Cerullo, D., Sennah, K., Azimi, H., Lam, C., Fam, A., & Tharmabala, B. (2013). Experimental study on full-scale pretensioned bridge girder damaged by vehicle impact and repaired with fiber-reinforced polymer technology. *Journal of Composites for Construction, 17*(5), 662-672.

Chajes, M.J., Chacon, A.P., Swinehart, M.W., Richardson, D.R., Wenczel, G.C., & Liu, W. (2005). *Applications of advanced composites to steel bridges: a case study on the Ashland Bridge (Delaware-USA)*.

Davalos, J., Chen, A., Ray, I., & Levan, J. (2012). Comprehensive study on using externally bonded FRP composites for the rehabilitation of reinforced concrete T-beam bridges. *Journal of Infrastructure Systems, 18*(2), 89-102.

Eamon, C.D., Wu, H., Makkawy, A.A., & Siavashi, S. (2014). Design and construction guidelines for strengthening bridges using fiber reinforced polymers (FRP).

Gentile, C., Svecova, D., Saltzberg, W., & Rizkalla, S.H. (2000). FRP strengthening for timber bridges. International Composites Conference, 2nd, Sydney, New South Wales, Australia: p. 228-33.

Harik, I.E. & Peiris, A. (2014). 16 years of deployment of FRP material in bridges in Kentucky. Paper presented at Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment. Abstract retrieved from: http://trid.trb.org/

Harries, K.A. & El-Tawil, S. (2008). Steel-FRP composite structural systems. Composite Construction in Steel and Concrete VI: pp. 703-716. ASCE.

Peiris, A., & Harik, I. (2015). Steel bridge girder strengthening using postinstalled shear connectors and UHM CFRP laminates. *Journal of Performance of Constructed Facilities, 29*(5), 04014139.

Figure 27. Technology Information PDFs: Bibliography. [268]

APPLICATION OF FRP: EXTERNAL BONDING

REFERENCE MATRIX

KEY: x = item addressed in reference	Application	Experimental Testing	Flexural Strengthening	Shear Strengthening	Deck Strengthening	Concrete Strengthening	Steel Strengthening	Timber Strengthening	Lightweight Decks	Structural Modification	Analysis Technique	Design Procedure	Fatigue Behavior	Impact Damage	Anchorage
Bologna & Khabra (2012)	x			x		x									
Cerullo et al. (2013)		x	x			x								x	x
Chajes et al. (2005)	x	x	x				x								
Davalos et al. (2012)	x	x	x			x					x				
Eamon et al. (2014)			x			x						x			
Gentile et al. (2000)		x	x					x							
Harik & Peiris (2014)	x			x		x									
Harries & El-Tawil (2008)		x	x	x			x						x		
Peiris & Harik (2014)	x		x				x								

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Improve Infrastructure Performance:
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Figure 28. Technology Information PDFs: Bibliography-Reference Matrix.

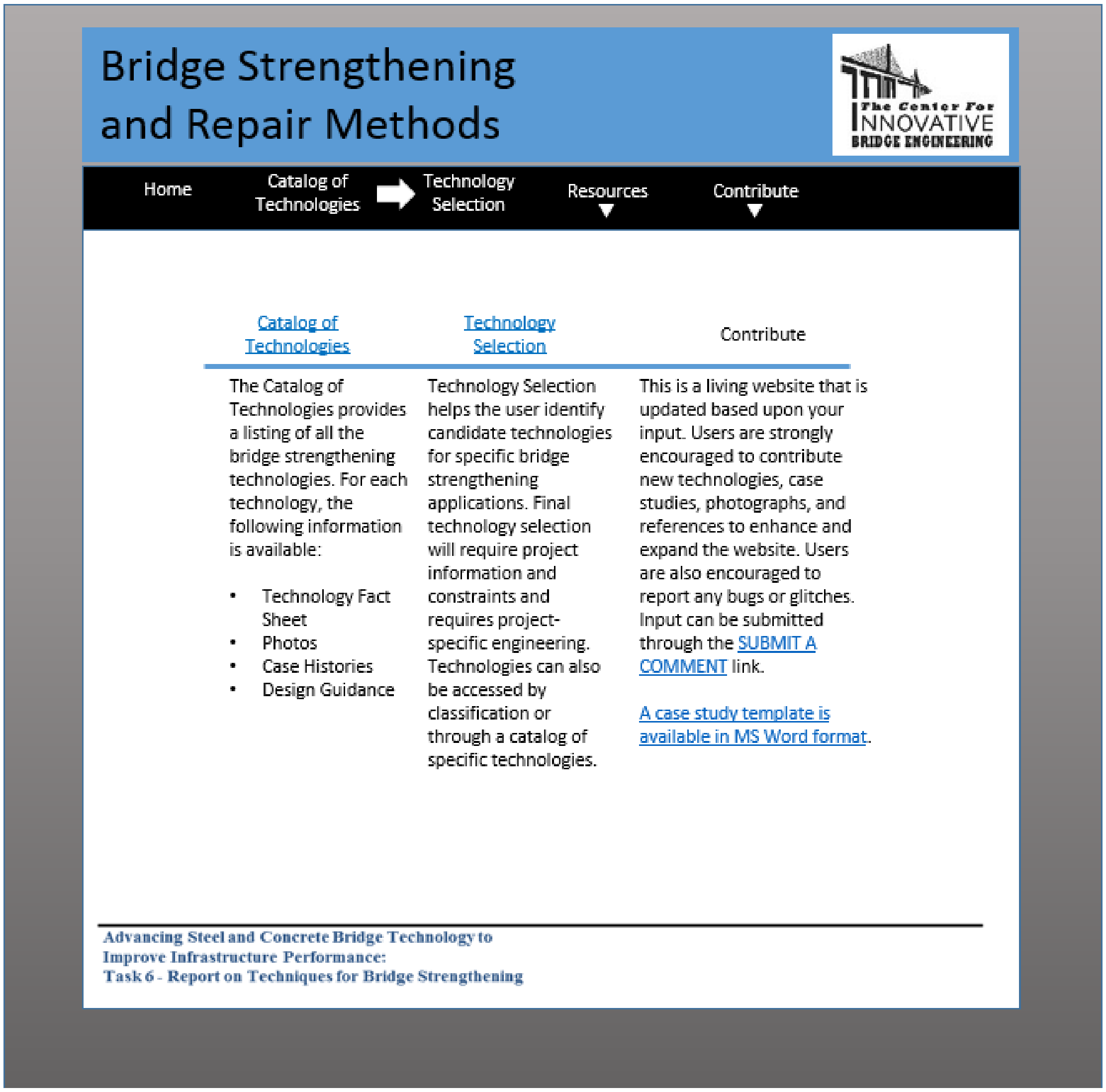


Figure 29. Home Page: Technology Selection Tab. [260]

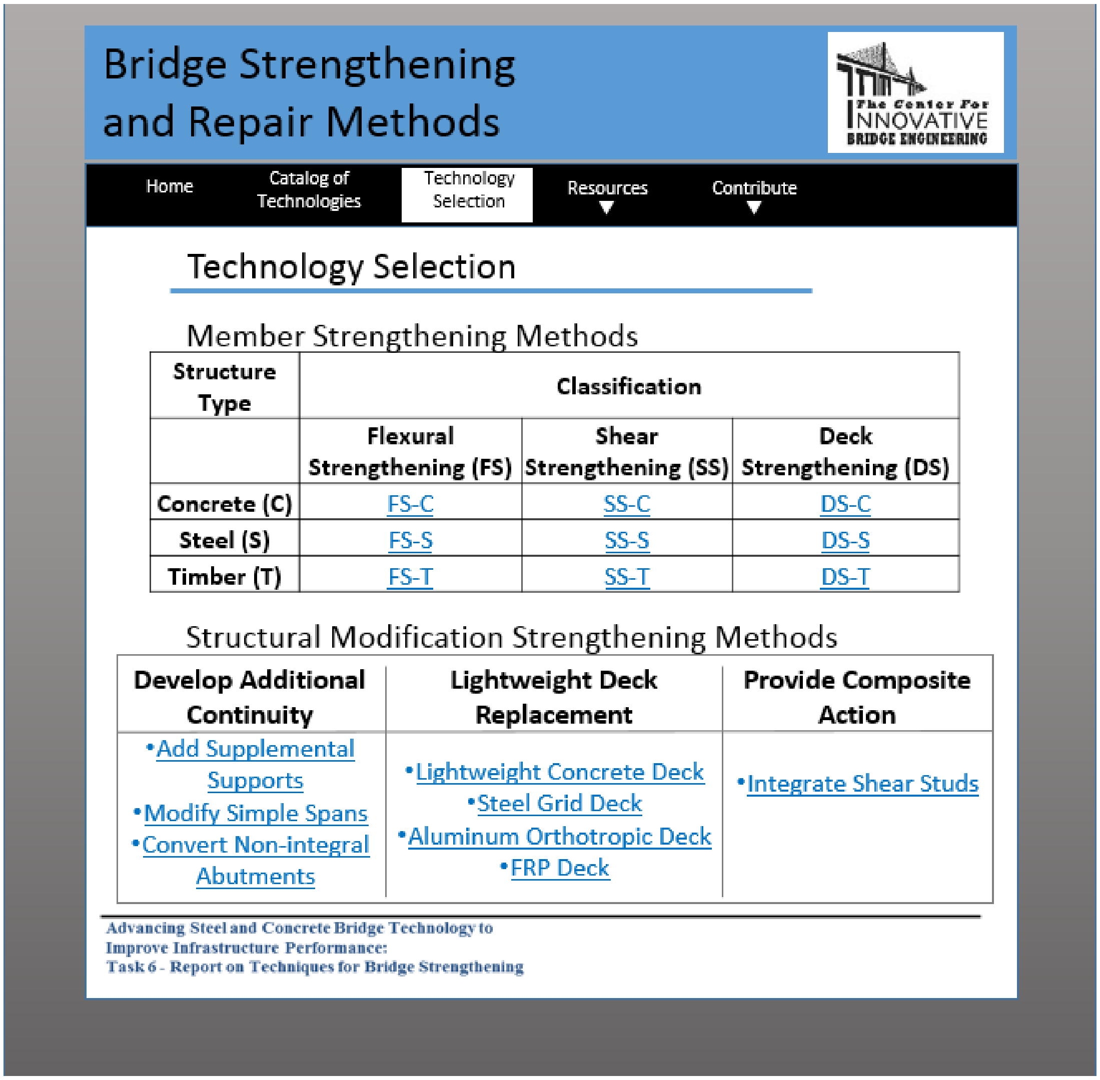


Figure 30. Technology Selection Main Page.

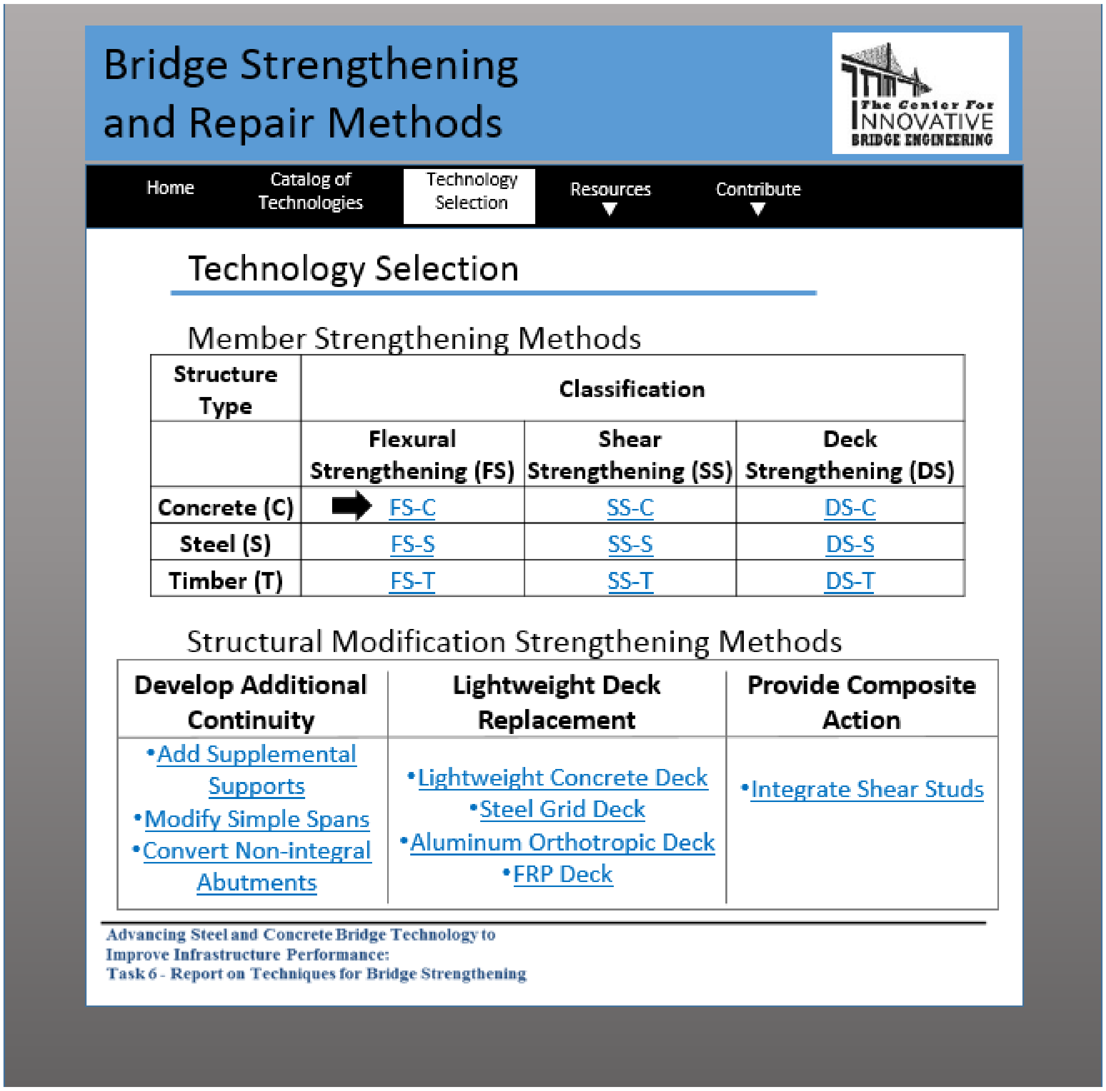


Figure 31. Technology Selection: Choose a Matrix Option.

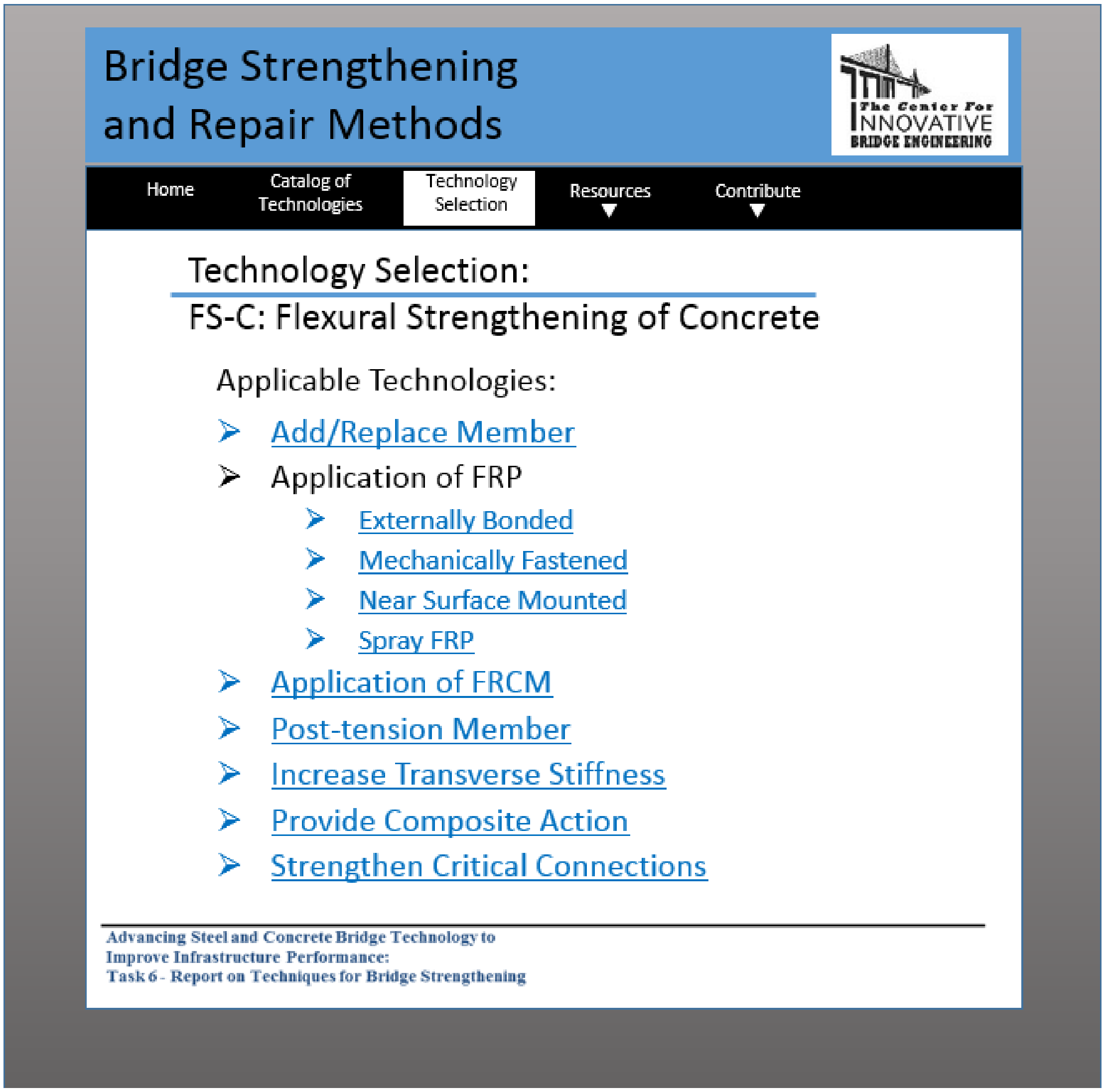


Figure 32. Technology Selection: List of Applicable Technologies.

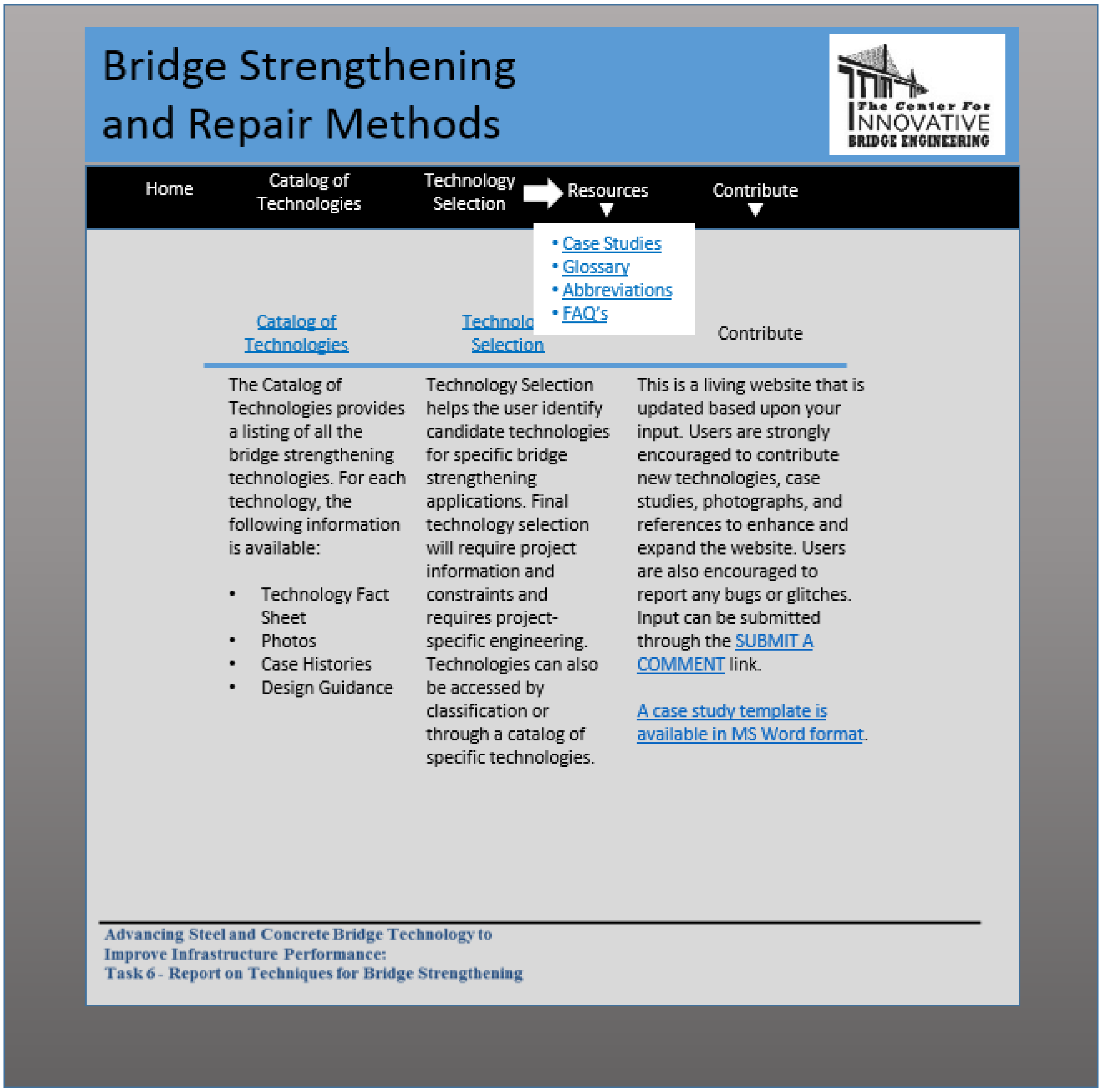


Figure 33. Home Page: Resources Tab and Drop-down Menu. [260]

Figure 34. Resources: Case Studies. [261]

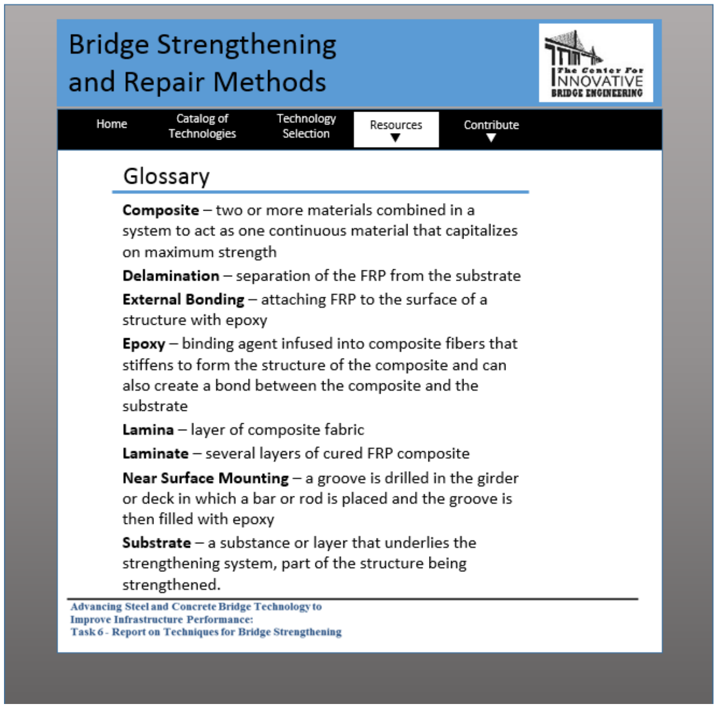


Figure 35. Resources: Glossary.

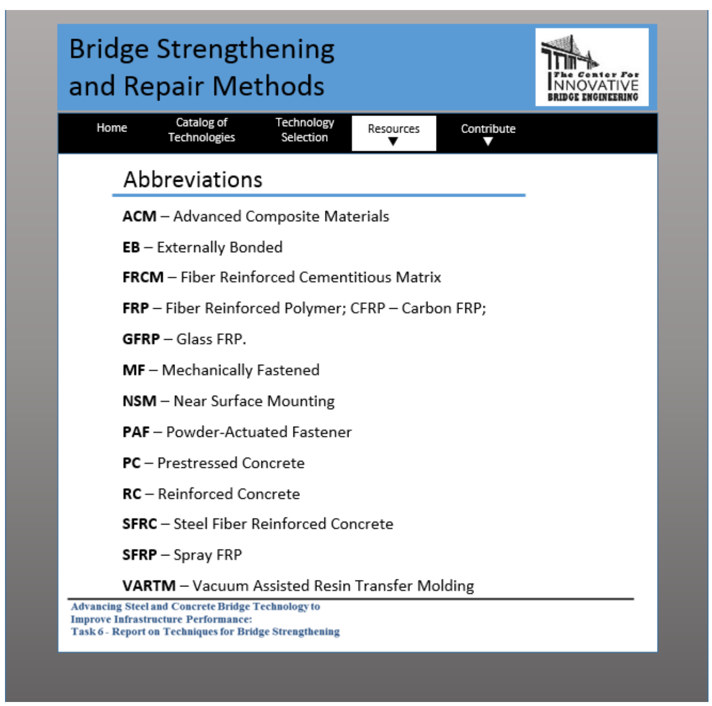


Figure 36. Resources: Abbreviations.

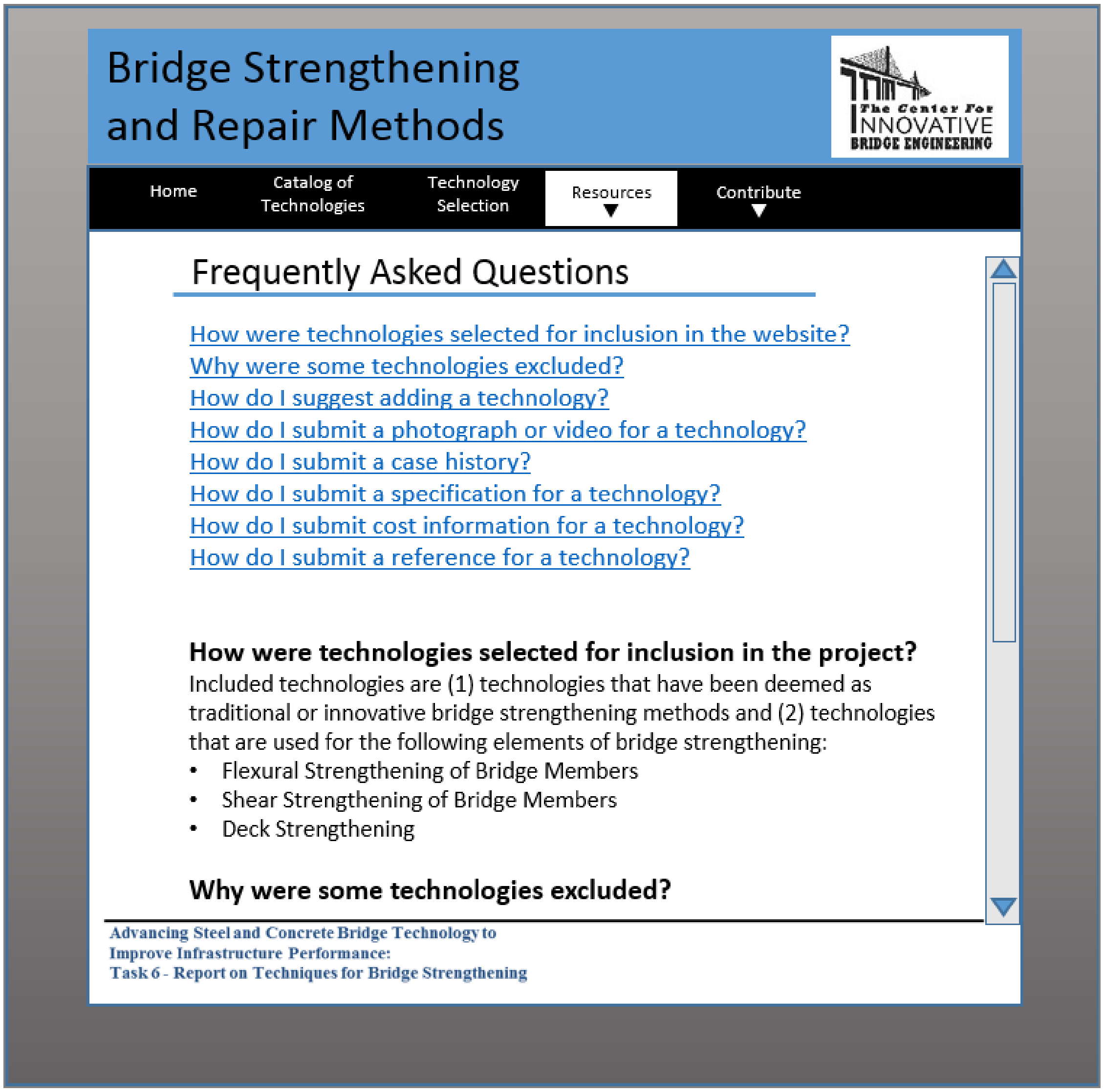


Figure 37. Resources: Frequently Asked Questions.[269]

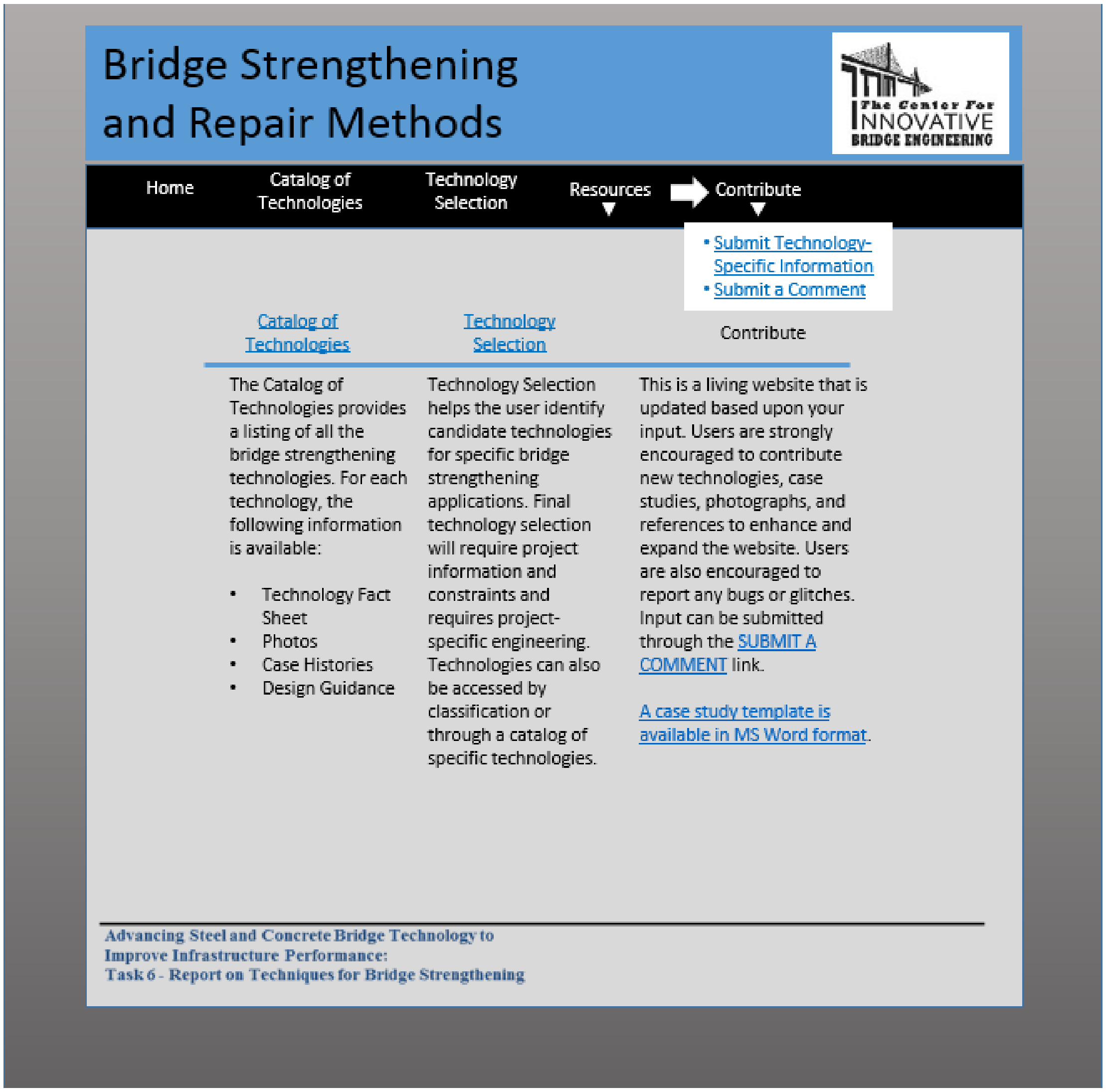


Figure 38. Home Page: Contribute Tab and Drop-down Menu. [260]

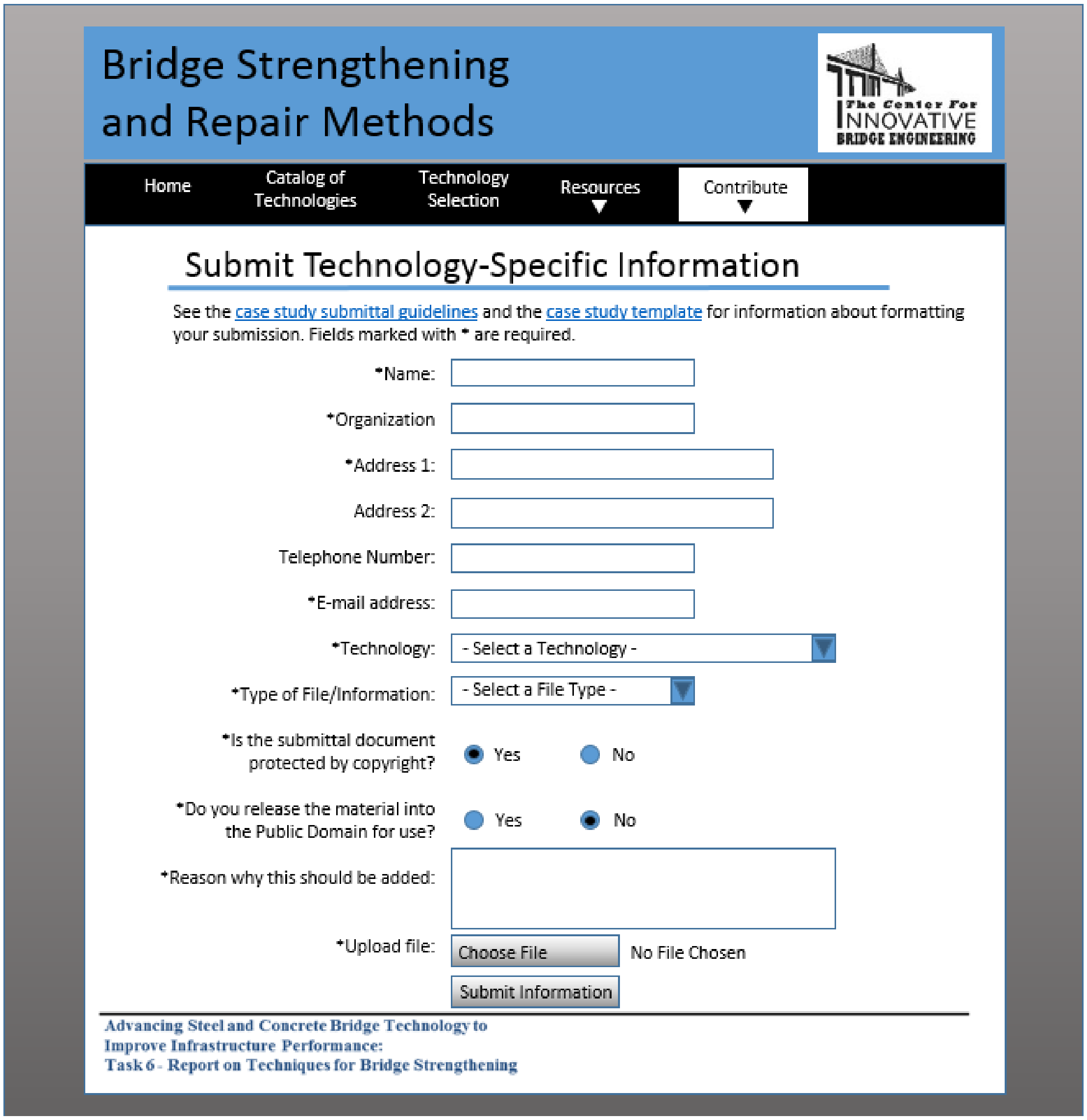
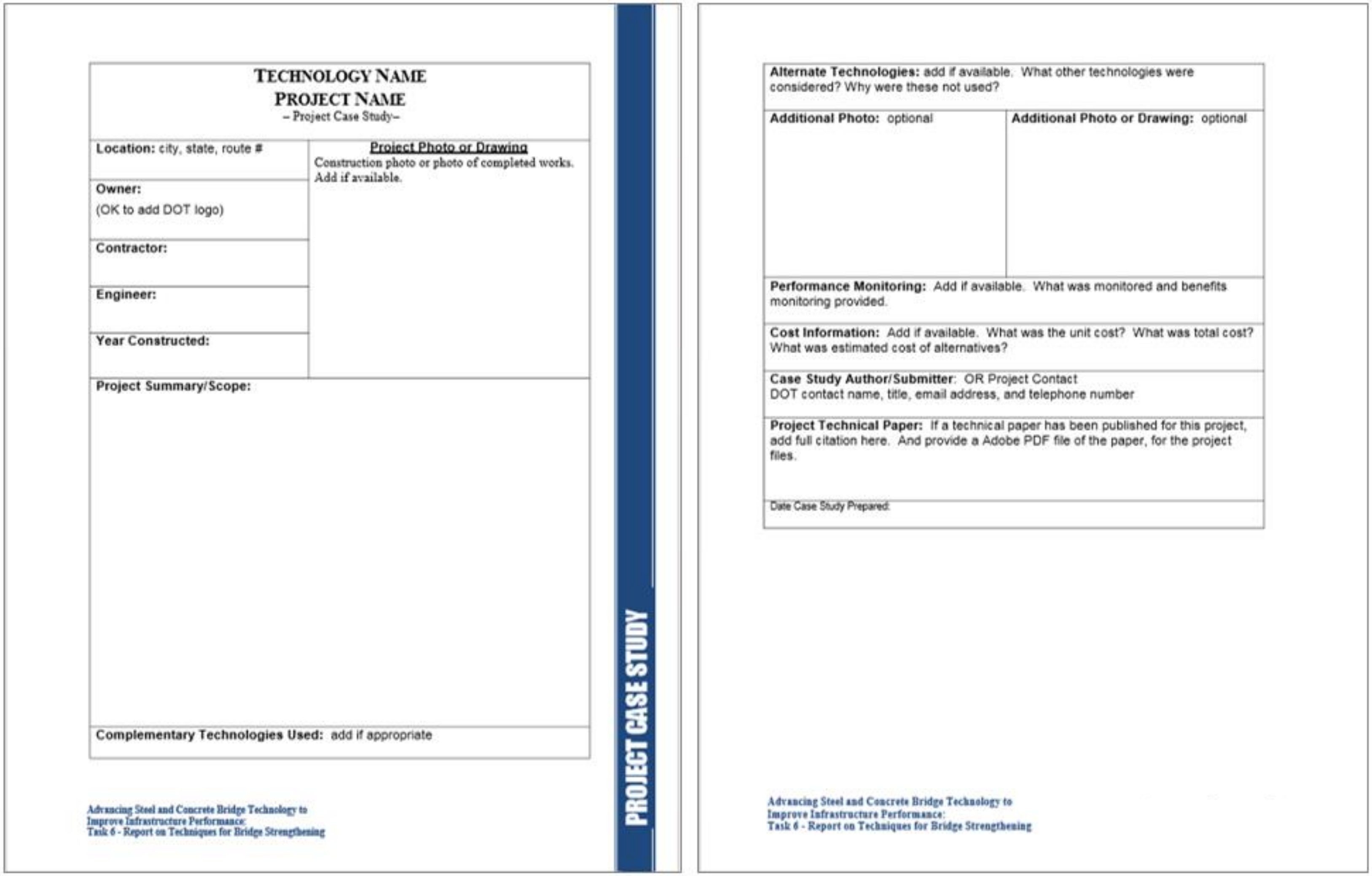


Figure 39. Contribute: Submit Technology-Specific Information Page.



TECHNOLOGY NAME
PROJECT NAME
– Project Case Study–

Location: city, state, route #

Owner:
(OK to add DOT logo)

Contractor:

Engineer:

Year Constructed:

Project Photo or Drawing
Construction photo or photo of completed works. Add if available.

Project Summary/Scope:

Complementary Technologies Used: add if appropriate

Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance:
Task 6 - Report on Techniques for Bridge Strengthening

PROJECT CASE STUDY

Alternate Technologies: add if available. What other technologies were considered? Why were these not used?

Additional Photo: optional

Additional Photo or Drawing: optional

Performance Monitoring: Add if available. What was monitored and benefits monitoring provided.

Cost Information: Add if available. What was the unit cost? What was total cost? What was estimated cost of alternatives?

Case Study Author/Submitter: OR Project Contact
DOT contact name, title, email address, and telephone number

Project Technical Paper: If a technical paper has been published for this project, add full citation here. And provide a Adobe PDF file of the paper, for the project files.

Date Case Study Prepared:

Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance:
Task 6 - Report on Techniques for Bridge Strengthening

Figure 40. Contribute: Case Study Submittal Template.

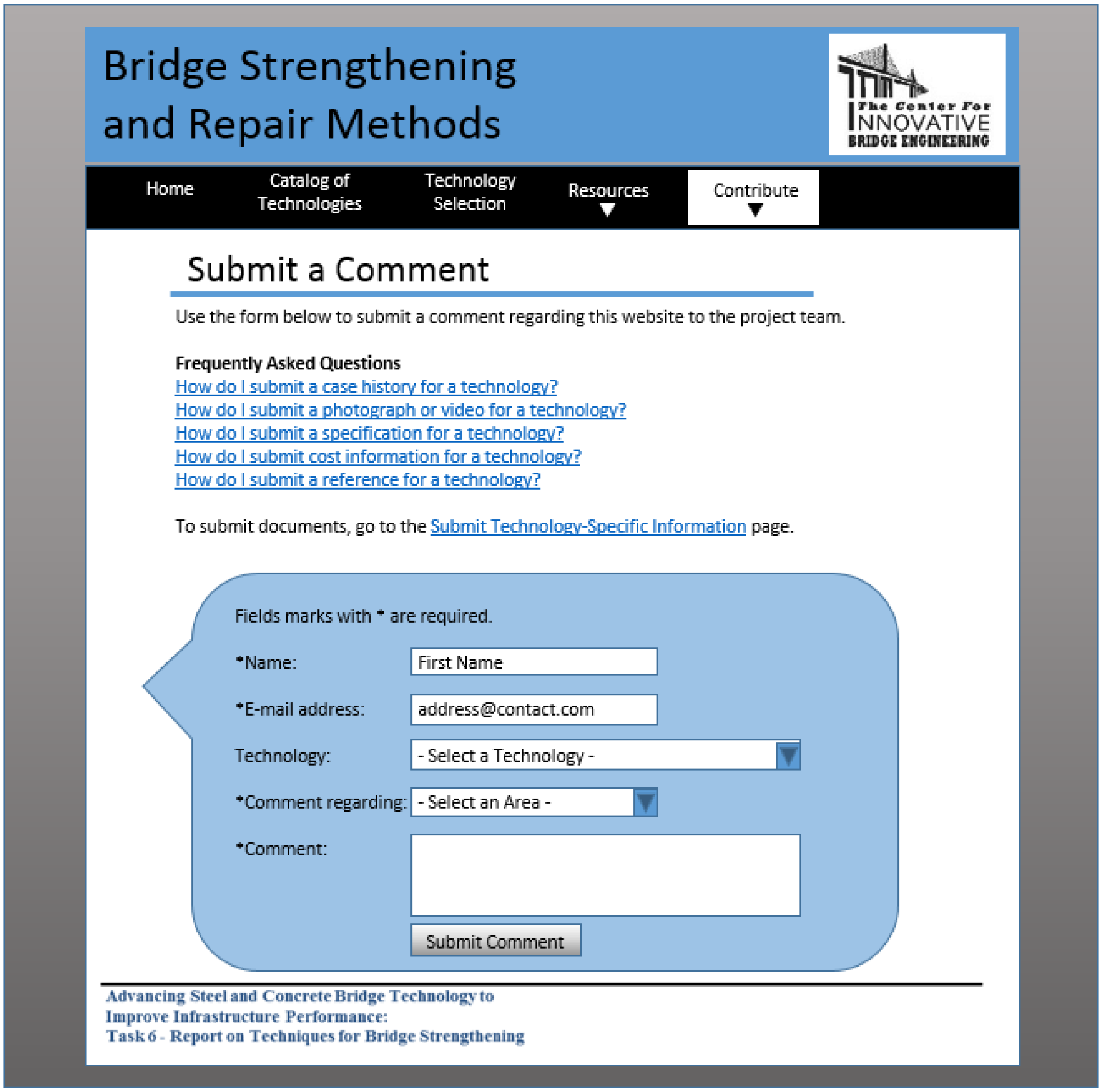


Figure 41. Contribute: Submit a Comment. [269]

Chapter 5

BRIDGE STRENGTHENING DESIGN EXAMPLES

5.1 Design Examples

Design examples provide guidance to a user on how a design procedure is performed for a specific project and provides the necessary equations and processes for the user to follow the same procedure for their own projects. As part of this project, design examples were produced for traditional bridge strengthening methods and innovative bridge strengthening methods. The traditional examples were contracted to Modjeski and Masters, a renowned bridge engineering firm headquartered in Mechanicsburg, PA. University of Delaware researchers adapted design examples which used innovative methods from design examples found in journal articles and design guides. After finding available design examples in the literature, and wanting to cover as many different bridge strengthening methods as possible, a total of eight design examples were produced, four using traditional materials and four using composite materials. A list of the design examples produced for this project is given below.

Design Examples using Composite Materials, adapted from the literature:

- Flexural strengthening of a concrete T-beam in an unstressed condition with FRP composites (*NCHRP 655*, [267]).
- Flexural strengthening of an interior RC beam with near surface mounted FRP bars (*ACI 440.2R-08*, [270]).
- Steel girder strengthened with high modulus CFRP strips [257].
- Lightweight deck replacement with an FRP deck [246].

Design Examples using Traditional Materials, developed by Modjeski and Masters:

- Truss strengthening with bolted cover plates (one compression member, and one tension member)
- Steel girder strengthening with bolted cover plates and web plates (flexural and shear strengthening)
- Increasing load carrying capacity during redecking multi-simple span bridge by making the deck composite with the girders and adding continuity between spans
- Concrete pier strut strengthening with post-tensioning bars.

The first example listed above, which details the design of an FRP strengthening system for a concrete T-beam, is included in Appendix B.3 of this thesis, and the other design examples will be found in an upcoming FHWA report based on this research. Other design examples using composite materials were also found in the literature, which included shear strengthening with FRP wraps and flexural strengthening of prestressed concrete beams [267, 270]. If the website framework is fully developed in future work, these other examples should also be adapted for inclusion in the website.

5.2 General Format for Bridge Strengthening Design Examples

The website framework developed and shown in Chapter 4 outlines that each bridge strengthening method should have a design example available to the user in PDF format for downloading. To make the design examples easy for users to navigate and compare, it is desirable for the design examples to follow a general format. This is why the design examples found in the literature search were adapted, to fit the format selected.

Presented first in the design example is a table that lists available specifications on the specific strengthening technology, listing the title, publication year, publication number (if applicable), and whether or not the publication is publically available for download.

The design example should follow the 'Summary of Design' listed in the general format, as follows:

The design example should begin with an *Introduction*, where the bridge data, material properties, and geometric properties are defined. The standard or specification that will be used in the design example is identified along with which load combinations the design example will address.

The *Solution* of the example will follow the following general steps:

Step 1. Calculate the existing nominal bridge capacity/resistance

Step 2. Calculate the desired bridge capacity

Step 3. Design the strengthening system

Step 4. Check the design against limits and requirements

A *Summary* is given at the end of the example, to give the dimensions and location of the strengthening system and how much capacity was gained.

More detailed steps of the design process can be listed as sub-steps under one of the four main steps listed above. For example, designing connectors for the strengthening system can be listed as a sub-step under Step 3, and checking the load combinations for strength I and fatigue limit states can be listed as separate sub-steps under Step 4.

Including figures and diagrams in the design example is strongly encouraged to help future users understand the geometry of the bridge being strengthened (ex. cross-sections) and the calculations being performed (ex. stress-strain diagrams). All equations and calculations should be easy to follow, guiding future users through the design process in such a way that the steps could be followed for a similar project.

If the design example uses variables that are not common (ex. variables specifically related to advanced composite materials), a list of definitions for these variables should be included at the beginning of the example. A full list of bibliographical references for all specifications referenced in the design example should also be included at the end of the PDF. This will provide future users with the information they need to access the same specifications.

Locating these design examples located in one place, such as a fully functional website, would provide a very valuable resource to bridge owners and bridge engineers. The design examples would show how the design procedures for new materials are similar to design procedures for traditional materials and also how they are different. They would also provide a starting point for bridge owners and engineers wanting to use new materials in their rehabilitation projects.

Chapter 6

SUMMARY

6.1 Review of Research Objectives

This research project had two main objectives. The first objective was to create a synthesis report which detailed the new bridge repair methods which were developed since the last comprehensive NCHRP report in 1997 [1]. The second research objective was to create a framework for a website which would be a repository for information on traditional and innovative bridge repair methods. The website was to include a decision matrix which would enable bridge owners and bridge engineers to more efficiently research options available to them and choose appropriate methods for their projects.

6.2 Literature Review Summary

To gather information on new bridge strengthening and repair methods that were developed and deployed in the field since the last synthesis report, we conducted an exhaustive literature review, reviewed the results of IBRC and IBRD projects, and gathered survey responses from AASHTO, FHWA, and TRB group and committee members. The major development found in bridge rehabilitation methods in the last twenty years was the use of composite materials, specifically fiber reinforced polymers (FRPs).

FRPs offer many benefits in bridge strengthening including their high strength-to-weight ratio and their resistance to corrosion and deterioration. FRPs can be applied as dry sheets on-site in order to accommodate unusual geometries, or they can be prefabricated in various different shapes including plates, rods, and deck panels. FRP plates can be externally bonded or mechanically fastened to strengthen girders or deck slabs. FRP rods can be used for post-tensioning or near surface mounting. FRP decks come in various configurations, including honeycomb, solid core, and hollow core sandwich panels.

The literature review also showed that some rehabilitation projects have used fiber reinforced cementitious matrix (FRCM) and sprayed FRP as their strengthening material. These strengthening methods were less well known by the survey respondents and were not used in any IBRC projects.

The literature review, survey results, and IBRC projects results all showed that external bonding of FRP sheets or plates is the most commonly known and implemented new method in the field. Rehabilitation projects that were found in the literature search included flexural strengthening, shear strengthening, and deck strengthening of concrete, steel, and timber bridges. Flexural strengthening of concrete bridges was the most common combination, but shear strengthening and steel strengthening are both increasing in popularity. Much of the rehabilitation work done on timber bridges yielded excellent results and provides a way to upgrade historical timber bridges and railroad bridges across the nation.

Many IBRC projects also used FRP decks. The IBRC projects created a foundation for future projects using innovative technologies. Not all the projects had positive results, but lessons learned about proper surface preparation, installation processes, and strength gained from innovative materials provide valuable information for the success of future projects using FRPs.

Survey results found that having a manufacturer representative on site during installation is critical to the success of the rehabilitation. Survey respondents also agreed that training materials, specifications, and design guidelines were needed to allow the use of FRP materials to become less expensive, less proprietary, and more mainstream as rehabilitation methods. Many specifications and guidelines for the application of FRP materials have been published in recent years (since 2006), as listed in Section 3.4.4.

Since composite materials are still new to the civil engineering industry, considerable research is still being conducted to improve their strength, composition, and long-term behavior in various settings. Application techniques are also being refined, from mechanical anchorages to vacuum assisted resin transfer molding. Composites are currently being used to strengthen arch structures and retrofit columns. The use of composites for improving impact damage, fatigue resistance, and torsional behavior of bridges is still under investigation. Many alternate applications for FRPs are also being researched. These applications include usage of FRP for steel buckling reinforcement, usage of FRP beams as load-bearing members, and usage of concrete-filled FRP tubes to construct arch bridges. These various areas of research demonstrate how versatile composite materials can be in the civil engineering industry.

6.3 Website Framework: Potential and 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. The motive behind the creation of a bridge rehabilitation website framework was to gather information on existing and evolving bridge strengthening methods in one place 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.

The website framework includes a flowchart, example pages for each level of the website, a list of traditional and innovative bridge strengthening and repair methods, and a case study submittal template. The flowchart demonstrates how pages of the website can be navigated, and will 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. The case study submittal template can be downloaded, filled out by users, and uploaded to add their project information to the website.

A major function of the 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. This website would provide a much more efficient means of gathering and distributing new information than creating time consuming 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.

6.4 Design Examples Summary

Eight design examples on different bridge strengthening methods were produced for this project. Four examples utilized traditional materials and were produced by Modjeski and Masters. The other four examples utilized composite materials and were adapted from examples found in the literature. All eight examples follow a general format for easy navigation and comparison. The general format is outlined in Chapter 5. One example detailing the design of an FRP strengthening system for a concrete T-beam is included in Appendix B.3 of this thesis. The other examples will be found in an upcoming FHWA report based on this research.

6.5 Recommendations for Future Work

Synthesis reports *NCHRP 293* (1987) and *NCHRP 249* (1997) on bridge strengthening were spaced a decade apart. This synthesis report is almost two decades after *NCHRP 249*. While the literature search revealed that substantial research was being conducted to develop new strengthening methods during that entire time frame, it was found that most of the field projects involving novel applications were completed in the last decade. This shows that it takes several years before research and development of new strengthening methods can be applied in the field, and several years after a new technology's introduction to become wide spread. Based on this observation, we recommend that future synthesis reports be spaced every 15 or 20 years instead of 10 years, to allow time for research, development, and implementation of new technologies.

The first objective of this research project was to conduct a literature review on new bridge strengthening methods. FRP near surface mounted bars and FRCM seem the most promising of the innovative strengthening methods, and future efforts should follow up on their development and implementation in future projects. The second objective of this research project was to create a website framework for bridge rehabilitation methods. Future efforts should focus on developing the framework into a fully functioning website. This project produced eight design examples to be included on the fully developed website, four using traditional materials, and four using composite materials. Future efforts should produce design examples for each bridge strengthening method listed on the website. Some design examples found in the literature were not adapted to the general format for this project, but could be adapted in future work. This project identified two possible hosts to maintain the site: TSP2 and University of Delaware. Future efforts should identify a permanent host for the website.

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Appendix A

MISCELLANEOUS LISTS AND INFORMATION

A.1 Traditional Bridge Strengthening Methods

Traditional bridge strengthening methods covered in NCHRP Reports 293 and 249

- Lightweight Deck to Reduce Dead Load
- Develop Composite Action
- Increase Transverse Stiffness
- Improve Member Strength
- Add/Replace Members
- Post-tension Members
- Strengthen Critical Connections
- Develop Additional Continuity

A.2 Survey Questions

1. Which of the following innovative bridge strengthening methods are you aware of?
    a. FRP sheet/plate bonding to increase flexural strength
    b. FRP sheet/plate bonding to increase shear strength
    c. FRP post-tensioning bars
    d. FRP deck panels
    e. Sprayed FRP
2. Please list any other innovative bridge strengthening methods you are aware of which were not listed in question 1.
3. Which innovative bridge strengthening methods have you had direct experience with?
    a. FRP sheet/plate bonding to increase flexural strength
    b. FRP sheet/plate bonding to increase shear strength
    c. FRP post-tensioning bars
    d. FRP deck panels
    e. Sprayed FRP
    f. Other (please specify)
4. What lessons have you learned from your direct experience with innovative bridge strengthening methods?
5. Do you have any other comments with regards to innovative bridge strengthening methods?

Appendix B

WEBSITE PDFs

B.1 Technology Fact Sheet

Technology Fact Sheet

APPLICATION OF FRP: EXTERNAL BONDING

August 2015 http://www.BridgeRehabMethods.org

FRP Strip Installation.

(Figure from Davalos *et al.* (2012) With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers)

Basic Function

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy to increase the structure's capacity in flexure and/or shear.

Advantages:

- Rapid installation: Curing time is a few hours
- Minimal Traffic closure, possibly not needed
- Increase in capacity with relatively little material
- No heavy lifting equipment required
- Can be applied by as few as two people
- Controls crack opening and propagation: improves member stiffness.

General Description:

External bonding of FRPs involves applying the composite material to the external face of a structure with a layer of epoxy. 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 to the structure when it cures.

Structural Applicability:

- Most commonly applied to concrete beams, but can also be bonded to steel girders, timber beams, truss structures, piers, columns, and the underside of decks.

Construction Methods:

First, the surface of the structure has to be prepared. The surface must be cleaned and roughened to ensure a good bond. Sometimes a priming agent may be applied to create a stronger bond. If using pre-cured plates, an adhesive layer of epoxy is applied to the structure's prepared surface, and the plates are put in place over the epoxy. Clamps are commonly used to hold the plates in place while the epoxy cures.

Dry fiber sheets can be used to accommodate varying structural surfaces, such as camber or wrapping around a bulb-tee beam. A layer of epoxy is applied to the structure, the fabric is smoothed over the epoxy and another layer of epoxy is applied over the fabric to saturate the fibers and create a continuous composite material.

Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance:
Task 6 - Report on Techniques for Bridge Strengthening

Additional Information:

Most external bonding is currently done by hand using the wet-layup technique. Vacuum-assisted resin transfer molding is an alternative way to apply externally bonded FRP. This requires machinery, but produces a higher quality composite that is stronger and more durable.

Example Successful Applications:

- Trout Brook Bridge– New Brunswick, Canada
- I-A-92 over Walnut Creek-- Iowa
- KY 714 over Jeptha Creek-- Kentucky
- Steel Girder Bridge– Kentucky

Complementary Technologies:

Externally bonded FRPs are often anchored with Mechanical Fasteners to prevent or delay delamination. Externally bonded FRPs can also be prestressed to maximize the increase in capacity gained from the retrofit.

Alternate Technologies:

Mechanical fasters can be used alone instead of in conjunction with external bonding. Near Surface Mounting is an alternate strengthening technique. Post-tensioning bars can also be used as an alternative.

Potential Disadvantages:

- Potential peeling or delamination of material
- More expensive than traditional repair materials
- Material has a proprietary nature, but specifications have been published to minimize the variability of retrofits.

Key References for this Fact Sheet:

Bologna, G., & Khabra, J. (2012). *Load rating upgrade of Trout Brook Bridge utilizing fiber reinforced polymer (FRP) composites*. Poster presented at the 2012 Conference and Exhibition of the Transportation Association of Canada – Transportation: Innovations and Opportunities, Fredericton, New Brunswick, Canada.

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B.2 Example Case Study

GFRP Fabric U-Wrap
Trout Brook Bridge

– Project Case Study –

Location: Victoria County, New Brunswick, CA, Route 109

Owner:

New Brunswick Department of Transportation and Infrastructure

Contractor:

Engineer:

Year Constructed: 2011

Project Photo or Drawing

Trout Brook Bridge finished repair (Photograph from Bologna & Khabra (2012))

Project Summary/Scope:

The objective of the Trout Brook Bridge retrofit was to provide additional shear capacity to the critical shear zones of all four girders at both ends. New Brunswick Department of Transportation required an increased load rating on their bridge to allow for the transport of heavier vehicular loading. Through analysis the Department of Transportation determined that in order to increase the bridge's load carrying capacity from 43,500 kilograms to 50,000 kilograms, each girder would have to be strengthened by a minimum of 120 kN. Each beam was strengthened to provide an increase in 120 kN for a specified length of 5 meters at each end. An effective and durable glass composite FRP was selected, with a single ply applied at each location to achieve the desired strength requirement. The FRP wrap was applied transverse to the longitudinal axis of the beams, effectively creating a "U-Wrap."

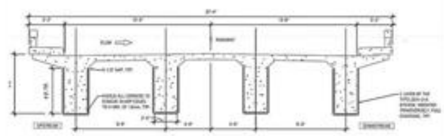
Prior to FRP application, however, all cracking issues had to be repaired.

Note: All composite materials were designed per CSA S6-06 standards.

Complementary Technologies Used: Mechanical grinders used for surface preparation. Epoxy crack injection used to repair girders prior to FRP bonding.

Advancing Steel and Concrete Bridge Technology to
Improve Infrastructure Performance:
Task 6 - Report on Techniques for Bridge Strengthening

PROJECT CASE STUDY

Additional Photo:	Additional Photo or Drawing:
 Trout Brook Bridge girders (Photograph from Bologna & Khabra (2012))	 Trout Brook Bridge AutoCAD detail. (Photograph from Bologna & Khabra (2012))

Cost Information: Total project cost was approximately $80, 000.

Case Study Author/Submitter: Gaetano Bologna and Jeewan Khabra

Project Technical Paper: Bologna, G., & Khabra, J. (2012). *Load rating upgrade of Trout Brook Bridge utilizing fiber reinforced polymer (FRP) composites*. Poster presented at the 2012 Conference and Exhibition of the Transportation Association of Canada – Transportation: Innovations and Opportunities, Fredericton, New Brunswick, Canada.

Date Case Study Prepared: 8/10/2015

B.3 Design Example: Flexural strengthening of a concrete T-beam in an unstressed condition with FRP composites

APPLICATION OF FRP: EXTERNAL BONDING
DESIGN EXAMPLE

Preferred Design Procedure

The Federal Highway Administration (FHWA) has two documents for this technology that contain design guidance information. AASHTO also has a guide specification for this technology:

Publication Title	Publication Year	Publication Number	Available for Download
AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 1st Edition	2012	---	No
Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements	2010	NCHRP 655	Yes
Design of FRP Systems for Strengthening Concrete Girders in Shear	2011	NCHRP 678	Yes

Summary of Design/Analysis Procedure:

First, the bridge data, material properties, and geometric properties must be defined. It is also necessary to identify the standard or specification that will be used in the design along with which load combinations the design will address.
The solution of the example will follow the following general steps:

Step 1. Calculate Nominal bridge capacity/resistance

Step 2. Calculate desired bridge capacity

Step 3. Design Strengthening System

Step 4. Check Design against limits and requirements

A summary will be given at the end of the example, to give the dimensions and location of the strengthening system and how much capacity was gained.

Symbols and Notation

Variables used throughout the design example are listed alphabetically below:

A_{frp} = effective area of FRP reinforcement for shear-friction (in^2)

A_s = area of nonprestressed tension reinforcement (in^2)

b_e = effective width of beam (in)

d = effective depth of beam (in)

E_a = modulus of elasticity of adhesive (ksi)

E_c = modulus of elasticity of the concrete (ksi)

E_{frp} = modulus of the FRP reinforcement in the direction of structural action

E_s = modulus of elasticity of the nonprestressed tension reinforcement (ksi)

f_c' = 28 - day compression strength of the concrete (ksi)

f_{frp} = tensile strength of FRP reinforcement (ksi)

f_{peel} = peel stress at the FRP reinforcement concrete interface (ksi)

f_y = specified yield stress of steel reinforcement (ksi)

G_a = characteristic value of the shear modulus of adhesive (ksi)

h = depth of section (in); overall thickness or depth of a member (in.)

I_T = moment of inertia of an equivalent FRP transformed section, neglecting any contribution of concrete in tension (in^4)

k_2 = multiplier for locating resultant of the compression force in the concrete

L_d = development length (in)

l_{frp} = length of FRP reinforcement (ft)

M_n = nominal moment capacity of the beam (kip-in)

M_r = factored resistance of a steel-reinforced concrete rectangular section strengthened with FRP reinforcement externally bonded to the beam tension surface (kip-in)

M_u = factored moment at the reinforcement end-termination (kip-in)

n = number of required layers of FRP reinforcement

N_b = FRP reinforcement strength per unit width at a tensile strain of 0.005 (kips/in)

P_{frp} = Tensile strength in the FRP reinforcement at 1% strain

t_a = thickness of the adhesive layer (in)

t_{frp} = thickness of the FRP reinforcement (in)

T_{frp} = tension force in the FRP reinforcement (kips)

T_g = glass transition temperature ($°F$)

ε_c = strain in concrete

ε_{frp} = strain in FRP reinforcement

ε_{frp}^{tu} = characteristic value of the tensile failure strain of the FRP reinforcement

ε_{frp}^{y} = the strain in the FRP reinforcement when the steel tensile reinforcement yields

ε_o = the concrete strain corresponding to the maximum stress of the concrete stress-strain curve

ε_s = strain in steel

η = strain limitation coefficient that is less than unity .

v_a = Poisson's ratio of adhesive

τ_a = characteristic value of the limiting shear stress in the adhesive (ksi)

τ_{int} = interface shear transfer strength (ksi)

φ_{frp} = resistance factor for FRP component of resistance

Worked Design Example

Introduction: Flexural strengthening of a simply supported cast in-place reinforced concrete girder with FRP strips.

Reprinted from *Recommended guide specification for the design of externally bonded FRP systems for repair and strengthening of concrete bridge elements*, by A.H. Zureick et al., 2010, NCHRP 655, p.B-6 – B-18. Copyright [2010] by Transportation Research Board.

Bridge Data:
Span: 39 ft
Type: Cast in-place reinforced concrete
Year built: 1957
Location: State of Georgia

Material Properties
Concrete compression Strength: $f_c' = 3.9\ ksi$ (from in-situ testing)

Reinforcing steel yield strength: $f_y = 40\ ksi$

FRP reinforcement: Shop-fabricated carbon fiber/Epoxy composite plates
Plate thickness, $t_{frp} = 0.039$"
Glass Transition Temperature: $T_g = 165°\ F$
Tensile strain in the FRP reinforcement at failure: $\varepsilon_{frp}^{fu} = 0.013$
Tensile strength in the FRP reinforcement at 1% strain: $P_{frp} = 9.3\ kips / in$
Shear modulus of the adhesive = 185 ksi

Geometrical properties

Girder dimensions and Steel Reinforcement: See Figure 1.

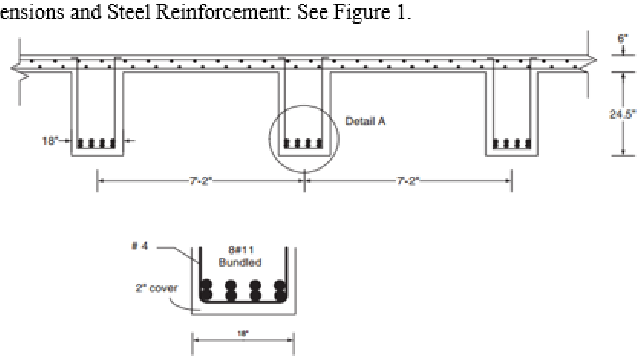


Figure 1. Bridge cross section at mid-span.

Note: For further clarity of figures see

http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_655.pdf

Determine Standards and Loadings

This example will use the Guide Specifications from NCHRP 655.

A Structural Analysis was run under the new loading and the following moments were given:

For Strength I Load Combination: M_D = 239 *kip-ft* and M_{L+I} = 615 *kip-ft*

For Fatigue Limit State: M_{L+I} = 308 *kip-ft*

Special Notes

Hydraulic jacking procedure of the bridge will be used so that strengthening is carried out in an unstressed condition.

Solution:

Step 1. Calculate the flexural strength of the T-beam

Effective depth

d = 30.5 - 2 - 0.5 - 1.41 = 26.59 *in.*

Effective Flange Width

As per Article 4.6.2.6.1 of AASHTO LRFD Bridge Design Specifications, the effective flange width is taken as the minimum of

- One-quarter of the effective span length;
- Twelve times the average depth of the slab, plus the greater of web thickness or one-half the width of the top flange of the girder; or
- The average spacing of adjacent beams.

$$b_e = \text{Minimum } \{ \frac{l_e}{4} = \frac{(39)(12)}{4} = 117\ in.$$
$$12t_s + b_w = 12(6) + 18 = 90\ in.$$
$$s = 86\ in.\ \}$$

b_e = 86 in.

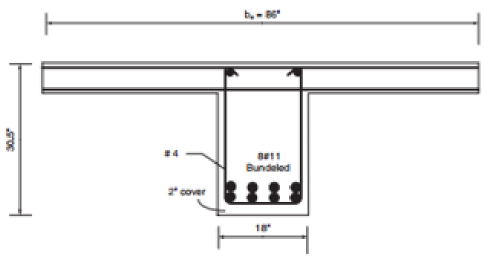


Figure 2. Reinforced Concrete T-beam.

Assumptions:

- A rectangular stress block to represent the distribution of concrete compression stresses (Article 5.7.2.2 of AASHTO LRFD Bridge Design Specifications),
- No contribution of the steel in the compression zone to the flexural strength,
- The strain in the tension steel is greater than the yield strain, and
- The neutral axis is located in the flange of the section

Thus, the compression and tension forces are $C_c = 0.85\, f_c' b_e a$ and $T = A_s f_y$, respectively, as illustrated in Figure 3.

From the condition of equilibrium of forces:

$0.85\, f_c' b_e a = A_s f_y$

Thus,

$$a = \frac{A_s f_y}{0.85 f_c' b_e} = \frac{12.48(40)}{0.85(3.9)(86)} = 1.75\ in.$$

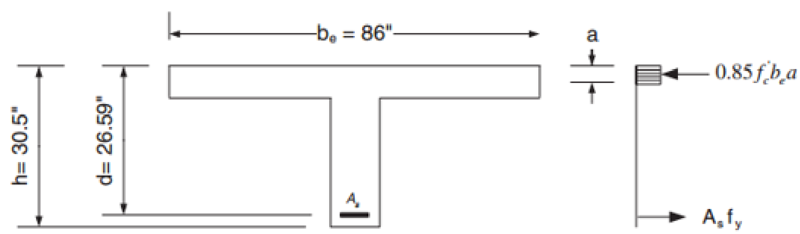


Figure 3. Force equilibrium on a reinforced concrete T-beam.

The depth of the neutral axis: $c = \frac{a}{\beta_1} = \frac{1.75}{0.85} = 2.06\ in.$

Since c = 2.06 in. < $t_s = 6\ in.$, the assumption that the depth of the neutral axis fall within the flange is appropriate.

Referring to Figure B-5, the strain in the tension steel can be computed as follows:

$$\frac{\varepsilon_s}{0.003} = \frac{d-c}{c}$$

$$\varepsilon_s = \frac{26.59 - 2.06}{2.06}(0.003) = 0.036$$

Since $\varepsilon_s = 0.036 > \frac{f_y}{E_s} = \frac{40}{29{,}000} = 0.00138$, the assumption that the tension steel yielded is correct.

The nominal flexural strength of the girder can then be computed from

$$M_n = A_s f_y \left(d - \frac{a}{2}\right) = (12.48)(40)\left(26.59 - \frac{1.75}{2}\right) = 12{,}837\ kip - in.$$
$$\emptyset M_n = 0.9(12{,}837) = 11{,}553\ kip - in.$$

Check compliance with Article 1.4.4 of the proposed Guide Specifications
$\emptyset M_n = 11{,}553\ kip - in. > M_D + M_{L+I} = 239 + 615 = 854\ kip - ft = 10{,}248\ kip - in.$

Proceed with the design of an externally bonded FRP reinforcement system.

Step 2. Calculate the desired capacity of the T-beam

The moment capacity of the strengthened T-beam must exceed the moments given by the structural analysis:

For Strength I Load Combination: M_D = 239 *kip-ft* and M_{L+I} = 615 *kip-ft*

For Fatigue Limit State: M_{L+I} = 308 *kip-ft*

The factored moment for Strength I limit state is
$M_u = 1.25 M_D + 1.75 M_{L+I} = 1.25(239) + 1.75(615) = 1{,}375\ kip - ft = 16{,}500\ kip - in.$

Step 3. Design the FRP strip strengthening system

a. *Check FRP reinforcement material properties against specifications to ensure it can provide desired capacity.*

Determine if the FRP reinforcement material is in compliance with Section 2 (Article 2.2.4.1) of the Guide Specification and be sure that the glass transition temperature is higher than the maximum design temperature plus 40° F.

The maximum design temperature, $T_{MaxDesign}$, determined from Article 3.12.2.2 of AASHTO LRFD Bridge Design Specifications for the location of the bridge (State of Georgia)

$T_{MaxDesign} = 110° F$

$$T_{MaxDesign} + 40°\text{F} = 110°\text{F} + 40°\text{F} = 150°\text{F} < Tg = 165°\text{F}$$

Thus, Article 2.2.4.1 of the Guide Specification is satisfied.

Establish the linear stress-strain relationship of the FRP reinforcement based on the design assumptions specified in Article 3.2 of the Guide and compute the tensile strength corresponding to a strain value of 0.005. Results are presented in Figure 4.

$N_b = \frac{0.005}{0.01}(9.3) = 4.65\ kip/in$

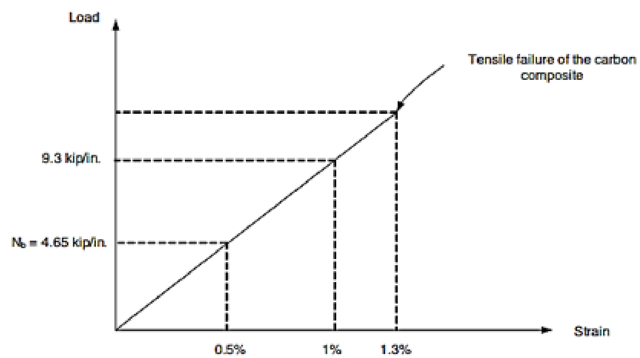


Figure 4. FRP reinforcement stress-strain diagram for design purposes.

b. Estimate the amount of FRP reinforcement required to accommodate the increase in flexural strength

For a preliminary estimate of the amount of FRP reinforcement necessary to resist 1,375 *k-ft* of moment, the following approximate design equation can be used:

$$T_{frp} \approx \frac{M_u - \emptyset M_n^{unreinforced}}{h} \approx \frac{(1{,}375 - 963)(12)}{30.5} = 162\ kips$$

$T_{frp} = nN_b b_{frp}$

Where n is the number of FRP reinforcement plates.

Use a reinforcement width of b_{frp} =14", the number of required layers is:

$$n = \frac{T_{frp}}{N_b b_{frp}} = \frac{162}{(4.65)(14)} = 2.5$$

Try 3 layers of the FRP reinforcement, for which T_{frp} = 3(4.65)(14) = 195.3 *kips*

Step 4. Check design against limits and required capacity

a. Compute the factored flexural resistance of the strengthened T-beam

<u>Location of the neutral axis</u>

The depth of the neutral axis can be determined from both strain compatibility and force equilibrium conditions as follows:

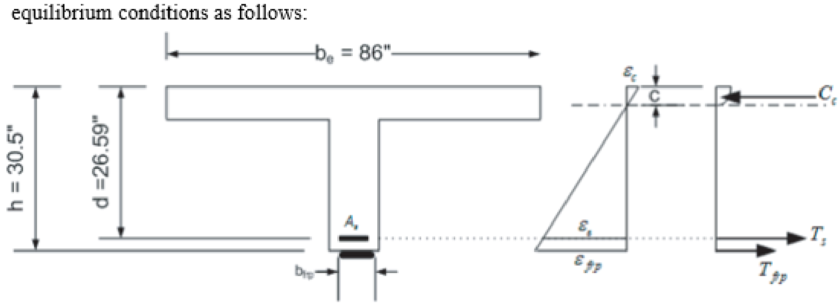


Figure 5. Reinforced concrete T-beam externally strengthened with FRP reinforcement.

Assume $c = 6$ *in.*

$\varepsilon_c = \frac{c}{h-c}(\varepsilon_{FRP}) = \frac{6}{30.5-6}(0.005) = 0.00122$

$E_c = 1{,}820\sqrt{f_c'} = 1{,}820\sqrt{3.9} = 3{,}594\ ksi$

$\varepsilon_o = 1.71\frac{(f_c')}{E_c} = 1.71\frac{3.9}{3{,}594} = 0.00186$

$\frac{\varepsilon_c}{\varepsilon_o} = \frac{0.00122}{0.00186} = 0.66$

$\beta_2 = \frac{Ln\left[1+\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right]}{\left(\frac{\varepsilon_c}{\varepsilon_o}\right)} = \frac{Ln\left[1+(0.66)^2\right]}{(0.66)} = 0.548$

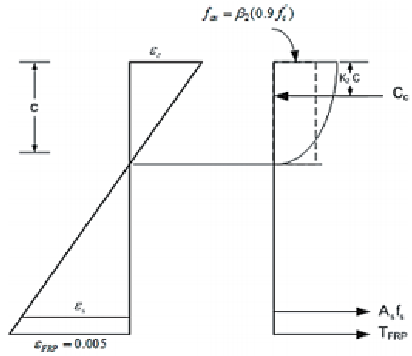


Figure 6. Strain and stress diagrams for the reinforced concrete T-beam externally reinforced with bonded carbon fiber FRP reinforcement.

Compression force in the concrete:

$$C_c = 0.9f_c'\beta_2 c b_e = 0.9(3.9)(0.548)(6)(86) = 992.5\ kips$$

Tension Force in the tension steel:

Strain in the steel:

$$\varepsilon_s = \frac{d-c}{c}\varepsilon_c = \frac{26.59-6}{6}(0.00122) = 0.00418 > \varepsilon_y = \frac{f_y}{E} = \frac{40}{29{,}000} = 0.001379$$

Thus,

$$T_s = A_s f_y = (12.48)(40) = 499.2\ kips$$

Tension Force in the FRP reinforcement:

$$T_{frp} = 3(4.65)(14) = 195.3\ kips$$

Total Tension Force

$$T = T_{frp} + T_s = 195.3 + 499.2 = 694.5\ kips$$

Clearly equilibrium of the forces is not satisfied $C_c - T = 992.5 - 694.5 = 298$ *kips*, and the assumed depth for the neutral axis ($c = 6$ *in.*) is incorrect. By trial and error, one can find that by assuming a depth of the neutral axis, $c = 4.96$ *in.* , and repeating the above calculations, the following values are computed:

APPLICATION OF FRP: EXTERNAL BONDING

DESIGN EXAMPLE

For $c = 4.67$ *in.*

$\varepsilon_c = 0.00097,\quad \varepsilon_s = 0.0042 > \varepsilon_y,\quad \frac{e_c}{e_o} = 0.53,\quad \beta_2 = 0.46,\quad Cc = 695.2\ kips,$
$T_s = 499.2\ kips,\quad T_{frp} = 195.3\ kips,$
$T = T_{frp} + T_s = 195.3 + 499.2 = 694.5\ kips,$
$and\ \ Cc - T = 695.2 - 694.5 = 0.7\ kips,\ close\ enough\ to\ zero.$

<u>The factored flexural resistance</u>

$$M_r = 0.9[A_s f_s(d_s - k_2 c)] + \emptyset_{frp} T_{FRP}(h - k_2 c)$$

With $k_2 = 1 - \frac{2\left[\left(\frac{\varepsilon_c}{\varepsilon_o}\right) - \arctan\left(\frac{\varepsilon_c}{\varepsilon_o}\right)\right]}{\beta_2\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2} = 1 - \frac{2[(0.53) - \arctan(0.53)]}{0.46(0.53)^2} = 0.35\ \ and\ \ \emptyset_{frp} = 0.85$

$M_r = 0.9\left[(12.48)(40)\left(26.59 - (0.35)(4.97)\right)\right] + 0.85(195.3)[30.5 - (0.35)(4.97)] = 15{,}939\ kips - in.$

$M_r = 15{,}939\ kip - in. < 16{,}500\ kip - in.$

Increase the width of the FRP reinforcement to $b_{frp} = 17$ *in.* and re-compute the flexural resistance M_r

By doing so, we can find $c = 5.1$ in. and

$M_r = 16{,}930\ kip - in. > 16{,}500\ kip - in.$

Thus, AASHTO Strength I Load Combination limit is satisfied.

b. Check ductility requirements (Article 3.4.2 of the Guide)

When reinforcing steel first yields at $\varepsilon_s = \varepsilon_y = \frac{f_y}{E_s} = \frac{40}{29{,}000} = 0.00138$. For such a case, the strain and stress diagrams are shown in Figure 7.

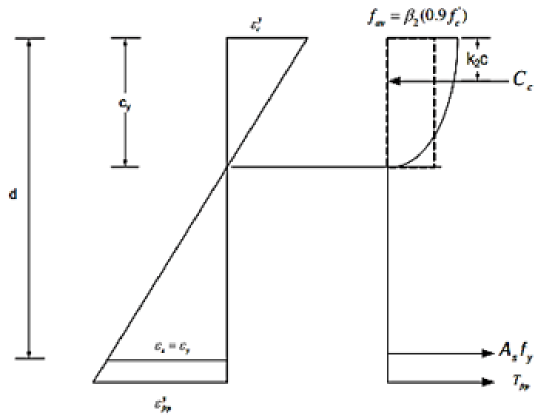


Figure 7. Strain and stress distribution in the T-beam when tension steel reinforcement yield.

By satisfying the conditions of force equilibrium and strain compatibility, the strain in the FRP reinforcement when the steel tensile reinforcement yields can be found numerically to be $\varepsilon^y_{frp} = 0.0016$. Thus, the ductility requirement of Article 3.4.2 of the guide specification is:

$$\frac{\varepsilon^u_{frp}}{\varepsilon^y_{frp}} = \frac{0.005}{0.0016} = 3.1 > 2.5.\ \boldsymbol{OK}$$

c. Calculate development length

Note: this step may be completed earlier in the design, but to save space on calculations, this step was completed after iterating the FRP area.

$$L_d = \frac{T_{frp}}{\tau_{int} b_{frp}} = \frac{237.15}{0.065\sqrt{3.9}(17)} = 109\ in. = 9.1\ ft$$

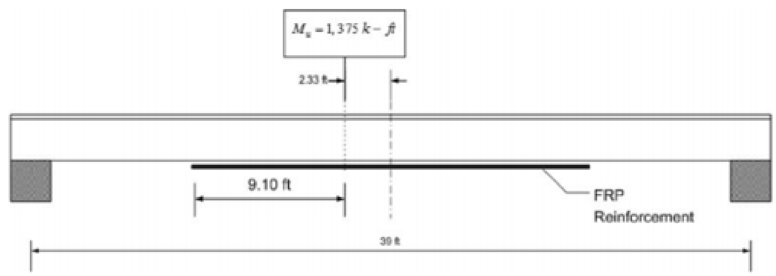


Figure 8. FRP reinforcement location.

Distance of FRP reinforcement end termination from the girder centerline = 9.10 + 2.33 =11.43 ft. Use 12 ft and reinforce symmetrically as shown in Figure B-10.

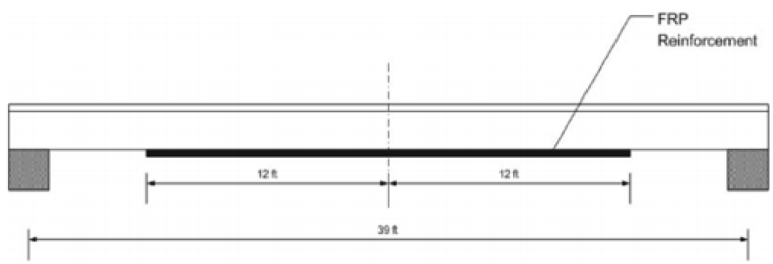


Figure 9. FRP reinforcement detail.

d. Check fatigue load combination limit state

For the fatigue load combination: $0.75ML_{+I} = 0.75(308) = 231\ kip - ft = 2{,}772\ kip - in.$

Determine the cracking moment: $M_{cr} = fr * \frac{I_g}{y_t}$ $with\ fr = 0.24\sqrt{f_c'} = 0.24\sqrt{3.9} = 0.474\ ksi$

Section Properties:
$I_g = 78{,}096\ in^4$
$y_t = 20.4\ in$
$M_{cr} = (0.474)\frac{78{,}096}{20.4} = 1{,}815\ kip - in. < 2{,}772\ kip - in.$

Neglect the concrete part in tension and calculate the moment of inertia of an equivalent transformed FRP section:

From the FRP reinforcement load-strain data:

$$E_{frp} = \frac{f_{frp}}{\varepsilon_{frp}} = \frac{N_b/tf_{rp}}{\varepsilon_{frp}} = \frac{4.65/(0.039)}{0.005} = 23{,}850\ ksi$$

Modular ratio for the concrete: $n_c = \frac{E_c}{E_{frp}} = \frac{3{,}594}{23{,}850} = 0.15$

Modular ratio of the steel: $n_s = \frac{E_s}{E_{frp}} = \frac{29{,}000}{23{,}850} = 1.2$

Based on the modular ratios for the concrete and for the steel, an equivalent FRP transformed section is ... ge.

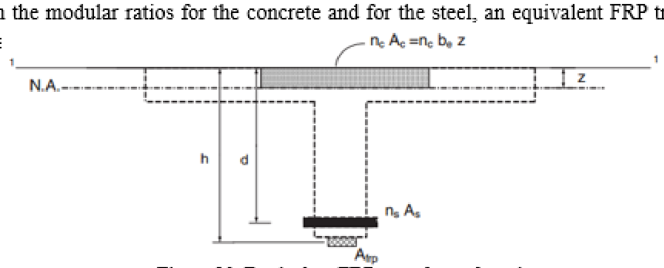


Figure 10. Equivalent FRP transformed section.

By summing the moment of areas about reference line 1-1:

$$A_{frp}\left(h+\frac{t_{frp}}{2}\right)+n_sA_sd+n_cA_c\left(\frac{z}{2}\right)=(A_{frp}+n_sA_s+n_cA_c)z$$

$$A_{frp}\left(h+\frac{t_{frp}}{2}\right)+n_sA_sd+n_cb_ez\left(\frac{z}{2}\right)=(A_{frp}+n_sA_s+n_cb_ez)z$$

$$z^2+\frac{2(A_{frp}+n_sA_s)}{n_cb_e}z-\frac{2\left[A_{frp}\left(h+\frac{t_{frp}}{2}\right)+n_sA_sd\right]}{n_cb_e}=0$$

$$\frac{2(A_{frp}+n_sA_s)}{n_cb_e}=\frac{2[(3)(17)(0.039)+1.2(12.48)]}{(0.15)(86)}=2.6\ in.$$

$$\frac{2(A_{frp}h+n_sA_sd)}{n_cb_e}=\frac{2\left[(3)(17)(0.039)\left(30.5+\frac{0.117}{2}\right)+(1.2)(12.48)(26.63)\right]}{(0.15)(86)}=71.22\ in^2$$

The equation ($z^2+2.6z-71.22=0$) has the solutions of z = 7.24 *in.* or z = 9.84 *in.* and only the positive solution z = 7.24 *in.* is valid. Because z = 7.24 *in.* > 6 *in.* , the assumption that the neutral axis fall in the flange was incorrect.

Assume that the neutral axis is located at a distance z > 6 *in.* By summing the moment of areas about reference line 1-1:

$$A_{frp}\left(h+\frac{nt_{frp}}{2}\right)+n_sA_sd+n_c(b_e-b_w)t_s*\frac{t_s}{2}+n_cb_wz*\frac{z}{2}=[A_{frp}+n_sA_s+n_c(b_e-b_w)t_s+n_cb_wz]z$$

$$z^2+\frac{2[(A_{frp}+n_sA_s+n_c(b_e-b_w)t_s]}{n_cb_w}z-\frac{2\left[A_{frp}\left(h+\frac{nt_{frp}}{2}\right)+n_sA_sd+n_c(b_e-b_w)t_s*\frac{t_s}{2}\right]}{n_cb_w}=0$$

By substituting all parameters into the above equation, the following equation is obtained

$$z^2+57.9z-476.4=0$$

Which has a positive solution z = 7.31 *in.*

The moment of inertia of the equivalent transformed FRP section can be computed to be I_T = 8,345 $in.^4$

Strain in the concrete, steel reinforcement, and FRP reinforcement, respectively, due to the fatigue load combination:

$$\varepsilon_c = \frac{M_f z}{I_T E_{frp}} = \frac{(231)(12)(7.31)}{(8{,}345)(23{,}850)} = 0.00010 < 0.36\frac{f_c'}{E_c} = 0.36\frac{3.9}{3{,}595} = 0.00039$$

$$\varepsilon_s = \frac{M_f(d-z)}{I_T E_{frp}} = \frac{(231)(12)(26.63-7.31)}{(8{,}345)(23{,}850)} = 0.0003 < 0.8\varepsilon_y = 0.8\frac{40}{29{,}000} = 0.0011$$

$$\varepsilon_{frp} = \frac{M_f(h+tfrp-z)}{I_T E_{frp}} = \frac{(231)(12)[30.50+3(0.039)-7.31]}{(8{,}345)(23{,}850)} = 0.00032 < \eta\varepsilon_{frp}^u = 0.8(0.013) = 0.0104$$

e. Check reinforcement end termination peelings

The reinforcement end terminates at a distance of 19.5-12 = 7.5 ft from each of the end supports.

It is required to calculate the moment and shear at 7.5 ft from the end support. From analysis, we will use the following combinations:

$$M_u = 1.25MD + 1.75ML_{+I} = 503\ kip-ft$$
$$V_u = 1.25V_D + 1.75V_{L+I} = 112\ kips$$

Calculate the peel stress from the equation:

$$f_{peel} = \tau_{av}\left[\left(\frac{3E_a}{E_{FRP}}\right)\frac{t_{FRP}}{t_a}\right]^{1/4}$$

$$E_a = 2G_a(1+\nu_a)$$

$$\tau_{av} = \left[V_u + \left(\frac{G_a}{E_{frp}t_{FRP}t_a}\right)^{1/2} M_u\right]\frac{t_{FRP}(h-z)}{I_T}$$

$$\tau_{av} = \left[112 + \left(\frac{185}{(23{,}850)(0.117)(0.125)}\right)^{1/2}(503)(12)\right]\frac{(0.117)(30.5-7.31)}{8{,}345} = 1.5\ ksi$$

$$f_{peel} = (1.5)\left[\left(\frac{3(500)}{23{,}850}\right)\frac{0.117}{0.125}\right]^{1/4} = 0.740\ ksi > 0.065\sqrt{3.9} = 0.128\ ksi$$

Provide mechanical anchors at the FRP reinforcement ends.

Summary:

Externally bonded carbon FRP sheets were designed in this example. The FRP sheets are applied to the soffit of the RC T-beam along the longitudinal axis to increase the flexural capacity. The final design is summarized as:

Use number of plies of FRP sheets	$n = 3$
Use the width of FRP sheets	$b_{frp} = 17\ in.$
Use the length of FRP sheets, centered on the girder	$l_{frp} = 24\ ft.$
Use of end anchorage needed?	Yes
Final factored flexural resistance of T-beam	$M_r = 16{,}930\ kip - in.$

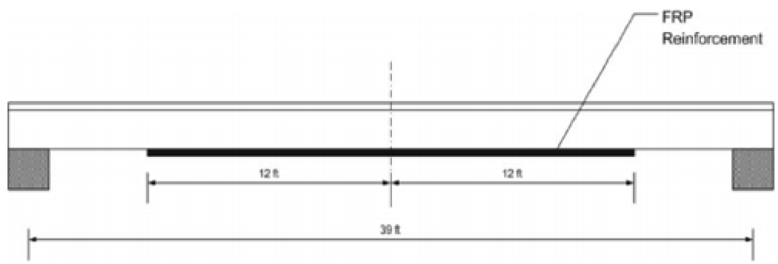


Figure 11. Final design of FRP strengthening.

References Page

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