



The Fundamentals for Fiber-Reinforced Polymer (FRP) Strengthening

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The Fundamentals for FRP Strengthening

United States infrastructure is aging. In its 2017 Infrastructure Report Card, the American Society of Civil Engineers (**ASCE**) issued a grade of C+ for the condition of the country's bridges. Of the 614,387 bridges in the country, almost **40 percent are 50 years or older** and about 10 percent are posted with a load restriction. So, what is the U.S. doing about this issue? As much as it can afford, but right now that isn't much—the nation's backlog of bridge rehabilitation needs is estimated at **\$123 billion**. ASCE reported that most bridges were designed for a lifespan of 50 years, so an increasing number will soon need major rehabilitation. Additionally, some studies indicate that the indirect costs of deteriorating infrastructure, when factoring in traffic delays and loss in productivity, could be as high as 10 times the cost to fix the structural damage.

Extending the life of a structurally deficient bridge through rehabilitation is almost always preferred over replacement. Compared to traditional repair methods using steel or concrete, fiber-reinforced polymer (FRP) materials are an ideal alternative. They are lightweight, corrosion resistant and have superior mechanical properties. FRPs compete with many strengthening techniques but are often the most attractive solution; though the actual materials are more expensive than the traditional options, the total construction cost is often cheaper.

History of FRPs

FRPs are known as advanced composite materials in the aerospace industry where they were adopted as an alternative to aluminum. The same characteristics valued by aerospace engineers (lightweight, durable and superior mechanical properties) have led to the adoption of FRPs as an alternative to steel and concrete in civil infrastructure. Since the introduction of FRPs nearly 30 years ago, the materials have successfully strengthened thousands of bridges, buildings, parking decks and other concrete and masonry structures. Throughout the years, FRPs have become an important strengthening technique in every engineer's toolbox. The material is externally bonded to or wrapped around existing concrete or steel members to increase their strength or seismic performance instead of using additional rebar or steel plates. Until recently, FRPs' use for restoring deteriorated steel structures was limited due to their low elastic modulus relative to steel. Now, ultra-high modulus carbon fibers, which are necessary for strengthening steel applications, are available through strand sheet applications.





Understanding how to use an FRP for structural strengthening, however, must first be accompanied by learning what constitutes as an FRP.

What is an FRP?

Fiber-reinforced polymer (FRP) is defined by the American Concrete Institute's ACI 440.2R, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, as the fibers and resins used to create the composite laminate, all applicable resins used to bond it to the concrete and any coatings used to protect the FRP. Simply put, FRP systems are like reinforced concrete where the fiber serves as the rebar and the polymer functions as the concrete.

Fiber Types

Carbon and E-glass are the most common types of fibers used in FRP strengthening systems. Fibers contribute to the strength and stiffness of an FRP and can also influence other FRP physical properties like durability, coefficient of thermal expansion (CTE) and density.

Carbon fiber reinforced polymers (CFRPs) are used in most strengthening or retrofitting applications. E-glass (GFRPs) are used by some Departments of Transportation (DOTs) to provide additional environmental protection to the structure, similar to a protective coating. All FRPs are linear elastic materials, so they do not yield, but possess sufficient elongation such that they can be used to strengthen a reinforced concrete member without losing much of the ductility of the member.

Resin Types

Polymers can be one of many resin types, but the most common are epoxy resins and polyurethanes. The jobs of the resin include:

- Holding the fibers in alignment
- Protecting the fibers from damage
- Transferring stress from fiber to fiber
- Influencing the durability of the FRP
- Providing resistance in a variety of chemical environments



RenewWrap® FRP Strengthening System



Fibers and polymers must be chemically compatible, so not all combinations result in a usable FRP material. Using a different resin type than what the fiber was manufactured to be compatible with can result in suboptimal performance. Epoxy resins, when combined with the fibers, are used to create the FRP and bond or adhere it to the concrete or steel substrate. Other resins, like polyurethanes, are sometimes used in confinement applications. The polymer protects the fibers and holds them in alignment, contributing to the overall durability of the FRP.

In addition to the fiber and resin variations, there are also various ways to install a FRP system.

Installation Types

FRPs are categorized as wet lay-up or pre-cured systems. Wet lay-up is the most common FRP form used in the United States. In this process, dry fabrics made with continuous fibers are wet out with a saturating resin in the field and adhered to or wrapped around an existing concrete member. The fabrics may be wet out directly on the members being strengthened or pre-saturated by hand or by a machine before being applied to the member. Heavier weight fabrics may need to be pre-saturated to ensure adequate impregnation of the fibers.

The most common reinforcing fabrics have unidirectional fibers, but multi-directional fabrics have been specified for various projects. Stacking piles or layers of unidirectional fabrics in different orientations is usually more cost effective than using multi-directional fabrics to provide reinforcement in more than one direction. This is no different than a rebar mat with bars in two orthogonal directions. Wet lay-up is used for strengthening all types of members because it can easily conform to the shape of a structure and wrap around members, like columns.

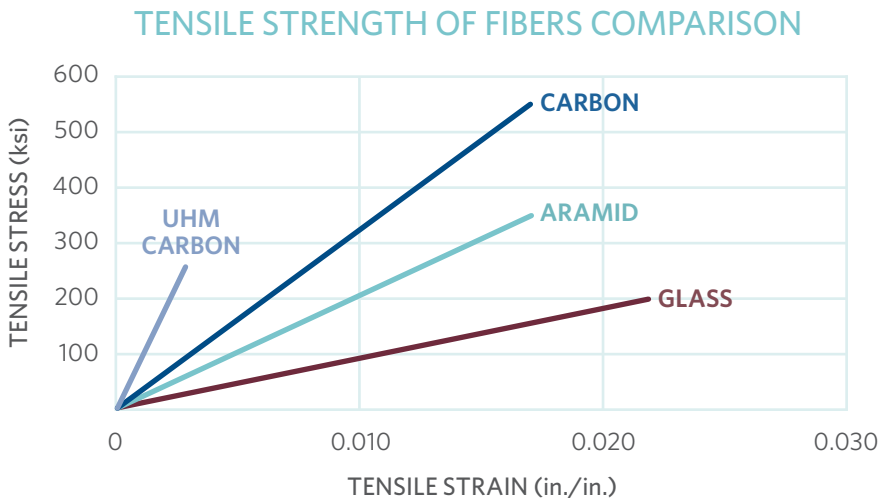
Pre-cured systems are composite plates — bars or other shapes manufactured off-site and bonded to the concrete or steel substrate with an adhesive, usually epoxy. These systems are rigid and cannot be used to wrap around a member. Near surface mounted (NSM) applications are ideal for strengthening negative moment regions on the tops of bridge decks for higher truck loads or larger barrier loadings. Shallow slots are cut into the surface of the concrete and filled with an epoxy adhesive and an FRP bar or strip. Pre-cured systems are most commonly used for flexural strengthening of slabs and beams, and in the United States, they are used to reinforce the tops of bridge decks in an NSM configuration to protect the FRP reinforcement from vehicles and snowplows. Since FRPs do not corrode like reinforcing steel, they can be placed very close to the surface of the concrete.

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Benefits of FRPs

FRPs offer superior tensile properties compared to traditional reinforcing materials and are extremely lightweight (**about 20% of steel**). The lightweight fabrics and easy installation contribute to overall cost savings on most projects by reducing the labor and equipment requirements. DOTs can accomplish more repairs with the same budget dollars. The thin and corrosion resistant material makes for durable and aesthetically pleasing repairs that are unnoticeable to the community once the material has been painted. Most projects can be completed without removing traffic loads from the structures contributing to further cost savings and reduced impact to local communities and users.



Compared to traditional repair methods using steel or concrete, fiber-reinforced polymer (FRP) materials are an ideal alternative. The material is externally bonded to or wrapped around existing concrete or steel members to increase their strength or seismic performance instead of using additional rebar or steel plates. They are lightweight, corrosion resistant and have superior mechanical properties.



Strengthening Concrete Structures

FRPs are used to strengthen or retrofit a wide range of structures. DOTs around the country commonly use FRPs to reinforce the following types of members:

- Arch Slabs
- Decks and Deck Overhangs
- Girders
- Pier Caps
- Pier Columns
- Piles
- Retaining Walls

Arch Slab Strengthening

FRPs may also be used to strengthen deck slabs and even arch slab bridges. An old, historic arch slab bridge in Ohio was recently retrofit by installing CFRP strips in a bi-directional pattern to provide strength across some of the cracked regions caused by water leaking from the road bed through the concrete. Projects like these require an understanding of the cause of the deterioration and an effective repair strategy that addresses it prior to strengthening.

Deck Strengthening

When the barrier or rail system of older bridges is upgraded, it usually requires the edge of a deck strengthened for additional negative moments and tension forces, which can be done using NSM techniques.

Girder Strengthening

CFRPs are used for shear strengthening of a concrete girder, including those damaged by truck impacts due to low clearance. This type of repair increases flexure and shear strength to restore lost capacity or support higher loads. The U-wraps can also confine concrete repairs made to corrosion-damaged girder ends or girders hit by trucks. Each state has its own standard details for CFRP girder repairs. Some wrap just the bottom flange of the girder while others wrap the complete height of the girder. Some require one layer with the fiber aligned vertically on the sides while others require two layers — one aligned vertically and one aligned horizontally. A standard detail for confining concrete repairs with FRPs is likely to emerge in the coming years as more DOTs employ this technique.



Indianola Avenue Arch Slab Bridge Repair in Columbus, OH



Clark County, MO Bridge Girder Repair



Pier Cap Strengthening

Many older bridges were designed to carry much lighter trucks than those using the highway system today. The condition of the piers may be good but may be undersized to carry today's trucks. Replacing the substructure can be very disruptive to communities and very expensive. It is becoming increasingly common for DOTs to use CFRPs to provide additional flexure and shear strength to the pier caps to support new decks and today's truck loads when re-decking the bridge. CFRPs are bonded to the bottom or sides to provide additional flexure strength and are wrapped around the pier cap (fully or three-sided) to provide additional shear strength.

Pier Column Strengthening

Strengthening pier columns can increase the strength or enhance the seismic behavior of bridge columns by providing additional confinement or shear reinforcement. Older bridges with inadequate confinement steel can easily be retrofitted to meet current seismic codes by simply wrapping the columns with CFRP.

In a case study, an inspection of all the columns and pier caps of an old interchange revealed various degrees of corrosion of the reinforcing steel, with the most severe occurring at construction joints. Cracks and small, localized delamination of sections of cover concrete were observed on many of the columns throughout the old interchange. These deficiencies were treated as potential hazards to both the traveling public and construction teams working around the structures. It was decided that an FRP system would be used for the repairs because of its light weight, ease of installation and lower cost of the repair, making it an ideal solution to prevent further spalling and increase structural strength for the remaining lives of the columns. A two-part resin was mixed and applied to the columns, then the dry carbon fiber-based fabric was wrapped around the columns with the fibers aligned horizontally to provide hoop strength. A second coat of epoxy was applied to the fabric for additional strengthening, which was then followed by a second layer of the FRP material to ensure long-term strength. The first column wrap was completed in less than six hours after making concrete repairs, and subsequent columns were strengthened even faster.

Once the FRP cures, an epoxy or latex acrylic top coat can be applied for aesthetic reasons and UV protection. Compared to encasing the existing columns in reinforced concrete or installing and welding steel jackets followed by grouting, it is not hard to see how FRPs offer cost benefits.



Garrett County, MD bridge Pier Cap Repair



Greenville County, SC Pier Cap and Column Repair



Strengthening Steel Structures

There are more than 20 years of research from around the world that shows FRPs to be effective at strengthening steel structures. FRPs are used to address a variety of deficiencies in steel structures caused by corrosion-related deterioration or increased loads. FRPs can restore section loss of tension and compression members such as flanges, bracing and truss chords. They provide additional compression strength to girder ends and additional shear strength of webs. The material increases member stiffness or localized stiffness and reduces service stresses in existing steel members to improve fatigue behavior. This repair method is an alternative to traditional steel strengthening techniques, which could be welding or bolting heavy steel plates to existing structures. FRPs, comparatively, require less equipment, are not susceptible to corrosion, have easier access to the repair and do not require welding to be used.

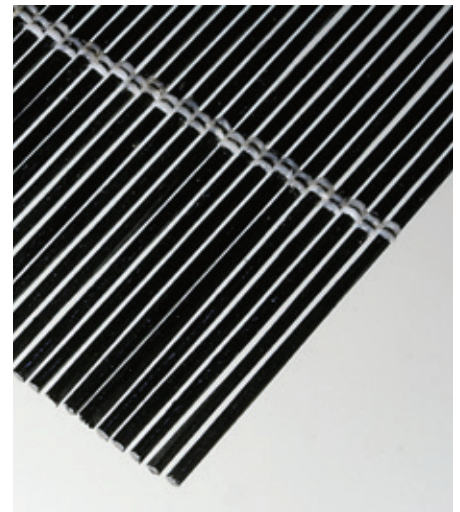
Carbon Fiber Strand Sheets

A new type of FRP system, strand sheets, was developed in Japan and used to strengthen concrete or steel members. Strand sheets combine wet lay-up features and traditional pre-cured plate FRP systems into a single system. This material was inspired by Japanese bamboo blinds — it consists of hundreds of pre-cured carbon fiber micro-rods assembled into a sheet bonded to a structure with epoxy resin. The resin allows the strand sheet to be uniformly bonded to an existing structure. The material can be spliced in the field by overlapping, like a wet lay-up system, and the quality of the bond line is visible by uniformity and complete coverage of carbon fiber strands.

The rehabilitation of the 1,090-foot-long Honjo Truss Bridge was one of the first strand sheet applications to a steel structure. This steel truss superstructure was weakened from the corrosion of truss members — where the diagonal members penetrated the concrete deck — and the sufficient section loss required strengthening. The deck was removed around the truss members and the carbon strand sheets bonded to the webs and flanges of the W-beams comprising the diagonal members. Thirty-six diagonal members were strengthened with strand sheets, and the area of the bridge was painted after the sheets were finished curing.



Steel bridge strengthening using carbon fiber strands sheets



RenewWrap® Strand Sheet



How to Inspect FRP Repairs

Engineers and DOTs often ask about how to inspect and accept FRP repairs. There are many methods that inspectors can use to determine if the FRP repair is acceptable. Visually, the inspector can verify if the contractor is following the correct installation procedure, verify the ply orientation and verify that the correct number of layers is applied. There are many inspection techniques employed on FRP projects, but it is important to specify these based on if the project is contact-critical or bond-critical and if it is a structural or non-structural application. A contact-critical application merely requires the FRP to be in intimate contact with the concrete member (e.g. column wrapping), while a bond-critical application requires the FRP to be well adhered to the concrete member to function as designed (e.g. deck strengthening for flexure or U-wraps for shear). Structural applications are ones that are designed to increase the strength or provide seismic upgrades to the structure. Non-structural applications are intended to provide additional protection like covering a recently repaired spall. Be careful about specifying inappropriate or nonrelevant inspection techniques.

INSPECTION	BOND-CRITICAL		CONTACT-CRITICAL	
	Structural	Protection	Structural	Protection
Visual	●	●	●	●
Sounding	●	●	●	●
Adhesion Testing	●	●	○	○
Witness Panels	●	○	●	○

Adhesion testing is used to verify if the FRP is well adhered to the substrate and if the surface was prepared correctly. Adhesion testing should be specified for all bond-critical projects. Witness panels, which are analogous to concrete cylinders, can be challenging to create in the field and must be tested by labs experienced in testing composites. To find undesirable delaminations, the inspector can use tap tests. Sounding inspections are used for all projects. A small delamination, which means they are less than 2 in², is permissible if the delaminated area is less than five percent of the FRP area or the number of delaminations is less than 10 per 10 ft². Larger delaminations can be repaired by selective removal or resin injection.



Conclusion

FRPs are an economical alternative to traditional strengthening techniques that are increasing in use for bridges through arch slabs, deck repairs, girder, pier caps, pier columns, piles and retaining walls. Their superior mechanical properties, corrosion resistance and lightweight design often lead to lower installation costs over cheaper, more traditional materials. Continue using FRPs with confidence!

If you are lacking confidence, however, or need more information on if FRP strengthening systems are the right choice for your project, Milliken Infrastructure Solutions, LLC is just a click or phone call away.

