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# Composites: Coming on Strong

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## Introduction

The use of advance composite materials in construction is an exciting and rapidly expanding market. Until only a few years ago, application of these materials to concrete structures was only the subject of research in the U.S. (Nanni 1993). Today, many companies are involved in the manufacturing, design, and installation of these systems in construction projects worldwide. Tens of projects in the U.S. alone have been completed accounting for millions of square feet of this material. In addition, accepted building codes for using composite materials are beginning to surface from organizations such as ACI and ICBO (ACI Committee 440, 1996; ICBO 1997). This material has quickly risen from state-of-the-art to mainstream technology.

The growth of this market is attributable to a decreasing trend of material and manufacturing costs combined with the ease and speed with which these materials may be installed. Composite strengthening systems have become very competitive with traditional strengthening techniques using steel. And while the market for these materials in new construction is somewhat limited, it is only a matter of time before FRP rebar and even FRP structural shapes become a commonplace alternative to steel.

## Materials

Fiber reinforced polymer (FRP) materials are composite materials consisting of high strength fibers in a polymer matrix. The fibers in an FRP composite are the main load-carrying element and exhibit very high strength and stiffness when pulled in tension. An FRP laminate will typically consist of several million of these thin, thread-like fibers. The polymer matrix (sometimes referred to as the resin) protects the fibers from damage, ensures that the fibers remain aligned, and allows loads to be distributed among many of the individual fibers in the composite. There are a variety of fiber types and resins that may be used to create an FRP composite. Fibers are selected based on the strength, stiffness, and durability required for the specific application, and the resins are selected based on the environment the FRP will be exposed to as well as the method by which the FRP is being manufactured.

Among several possibilities, the fiber types that are typically used in the construction industry are carbon, glass, and aramid (e.g., Kevlar™ is a commonly known type of aramid fiber). Carbon fibers are the stiffest, most durable, and most expensive fibers. Typical carbon fibers used in the construction industry have strengths exceeding 600 ksi – 10 times that of the typical Grade 60 steel used for reinforcement and over twice as strong as steel used for prestressing. The stiffness is similar to that of steel. Carbon is also quite resistant to most environmental conditions and can withstand high sustained and fatigue loading conditions. Carbon is, however, is a conductive fiber material; and while carbon itself will not corrode, if it comes in contact with steel, it will accelerate corrosion of the steel.

Glass fibers have lower strengths (typically around 400 ksi) and significantly lower stiffness but at a reduced cost. At present, one of the concerns with glass fibers is durability. Unprotected glass fibers degrade in most environments, especially hot/wet or highly alkaline environments. Glass is also susceptible to a phenomenon known as creep rupture. This phenomenon results in the eventual failure of the material under sustained loads higher than a fraction of the instantaneous ultimate load.

At present, aramid fibers are the least common in the construction industry. These fibers have similar characteristics between those of glass and carbon but with improved durability and excellent impact resistance (hence why they are often used to make bulletproof vests).

Resins used in FRP materials are generally classified as either thermosetting or thermoplastic resins. The construction industry almost exclusively utilizes thermosetting resins. These resins start as a low viscosity, flowable material that cures to a final solid form. Epoxy and vinyl ester are the most commonly used thermosetting resins because of durability and adhesion properties. Most thermosetting resins are sensitive to heat and ultra-violet light exposure. FRPs used in construction must be protected from heat (typically in excess of 160° F) and exposure to the sun.

## FRP Forms for Concrete Reinforcement

There is a seemingly endless variety of forms that FRP reinforcement for concrete can take. For new construction applications, FRP bars, grids, and tendons may be used (Nanni and Dolan, 1993). FRP bars are similar to steel rebar (often mimicking the shape and deformation patterns of rebar exactly). FRP grids are similar to welded wire fabric except that the grids may be three-dimensional. FRP tendons are used in place of steel tendons for prestressed concrete. The main advantage of FRP in new construction is durability. Since FRP materials do not corrode, FRP reinforced concrete may have an extremely long life. However, the cost of FRP materials is typically high in the new construction market and is only used in a limited number of applications.

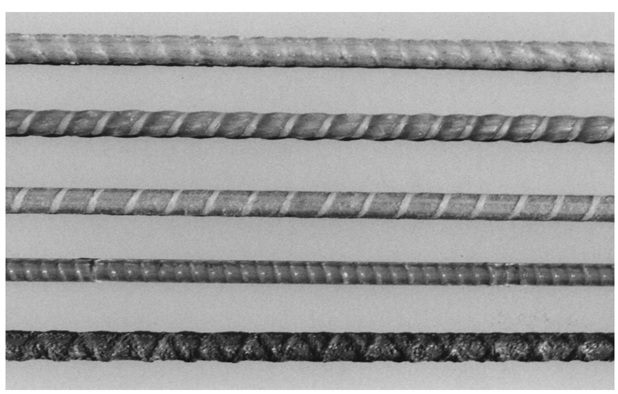

Figure 1: Some of the commercially available GFRP reinforcing bars (from top: Polystructures, International Grating, Hughes Brothers, Marshall Industries, Pultrall)

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In the U.S. market, the most widespread use of advanced composites in construction is in the concrete repair industry. Large construction product manufacturers like Master Builders and Sika supply FRP products. Other vendors, such as Sumitomo and Fyfe, offer FRP products. The most important characteristic of FRP in this application is the speed and ease of installation. Labor, shut-down costs, and site constraints typically offset the material cost of FRP making FRP strengthening systems very competitive with traditional strengthening techniques such as steel plate bonding and section enlargement. The durability and corrosion resistance of FRP are an additional benefit of these systems.

Some FRP strengthening systems come as pre-cured laminates in the form of plates or shells. Installation of these systems would be very similar to steel plate bonding for beams or steel encasement for columns. The systems are bonded to the concrete substrate (typically, mechanical anchorages do not work well for FRP systems) just as with steel plates, but the FRP systems are much lighter and do not require welding.

FRP strengthening systems may also be formed on site from the two constituent materials – fiber and resin. These systems are installed by a technique known as wet lay-up and consist of flexible sheets of the fiber material and uncured resins (the typical application uses a two-part epoxy resin). The fiber sheets may be a series of unidirectional fibers or a fabric woven from fibers in various directions. The resin is used both as the polymer matrix for the FRP and as the adhesive to bond the system to the concrete. The advantage of this system is that it may be formed in place around any surface shape.

## A History and Description of Industry

The idea of combining two different materials to make a single, superior composite material is not new. Some of the earliest building materials were composite materials. The ancient Egyptians reinforced their mud bricks with straw to make them stronger. Fiber reinforced polymers (FRPs) are just the latest version of this very old idea (Iyer and Sen, 1991).

Aerospace engineers have always searched for ways to reduce the weight of aircraft structures. They developed FRPs as lightweight materials with the strength and stiffness of the materials that they were accustomed to. The automotive, naval, defense, and sporting goods industries (to name a few) have since adopted the use of advanced composite materials on a widespread basis.

FRP is now being used in our industry to strengthen concrete and masonry structures. They compete directly with traditional strengthening techniques like section enlargement, external post-tensioning and steel plate bonding. Steel plate bonding is a method of strengthening a structure by bonding steel plates to the concrete surface in the areas of high tensile stresses. FRP originally began about 15 years ago in Japan and Europe as a low cost, low maintenance alternative to steel plate bonding.

FRP is currently being marketed in the form of systems. The system concept includes not only the materials (fibers and resins) but the R&D behind the product, technical support, design manuals, and contractor training.

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## Applications

FRP systems in the concrete repair industry are used to strengthen existing structures. Structures may need strengthening due to deterioration, design/construction errors, a change in use or loading, or for a seismic upgrade. FRP essentially works as reinforcement in concrete and provides strength where concrete is weakest – in tension. FRP may be used on beam or slab soffits to provide additional flexural strength, on the sides of beams to provide additional shear strength, or wrapped around columns to provide confinement and additional ductility (a primary concern in seismic upgrades). Among many other applications, concrete and masonry walls may be strengthened to better resist seismic and wind loads, concrete pipes may be lined with FRP to resist higher internal pressures, and silos and tanks may be strengthened to resist higher pressures.

Applications where existing FRP systems may not be useful include correcting punching shear problems in slabs or footings, correcting vibration problems, and providing greater compression strength to walls. In cases where FRP is useful, it should be recognized that there are reasonable limits to the additional strength afforded with FRP. Typically, increases in strength up to 50% are reasonable. It is also important to recognize that in cases where FRP is being used to address a deterioration problem, the FRP system will not stop the deterioration from occurring and may conceal visual signs of deterioration. The source of the deterioration should always be addressed and corrected prior to installing FRP. A common example is corrosion of steel reinforcement in a concrete beam or column. FRP should never be used to contain corrosion. FRP will not stop corrosion from progressing (the FRP may actually accelerate the corrosion process), and, in case of externally bonded FRP systems, the corrosion will eventually result in failure due to debonding.

In selecting the type of fiber to be used for an application, there are a few things to consider. Glass FRP is excellent for seismic upgrades where the seismic loads only temporarily engage the FRP. In cases where stresses are sustained in the FRP (such as in bending and shear strengthening), glass FRP should be avoided (or service stresses maintained at a minimum level) because of creep rupture effects. Carbon is much more suitable in these applications. Similarly in exterior applications, carbon FRP will be much more durable.

Fire protection is a concern when implementing an FRP system. Most FRP systems can achieve an ASTM E84 Class A fire rating for smoke density and flame spread with the application of a suitable coating. More importantly, FRP will not be capable of sustaining its structural properties under excessive heat due to a loss of composite action upon softening of the resin matrix. In critical applications, the FRP may be fireproofed with drywall containers or it may be possible to apply an intumescent fireproof coating, but these add significant expense and depending on the application may not be possible. The usual method to achieve the necessary structural fire rating is to use the FRP reinforcement as supplemental reinforcement. With this concept, the existing reinforced concrete structure will be capable of preventing total collapse without the FRP reinforcement. This is similar to the argument used for unbonded post-tensioning tendons that may have anchorages blow out during a fire.

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**Installation Procedure**

Installation procedures vary from system to system. For example, installation of Master Builders' MBrace system is done in a series of steps by the wet lay-up technique (See Figure 2). The first step includes surface preparation. The system relies heavily on the bond to the substrate, so it is critical that the surface be free of loose and unsound materials. Spalls should be removed and patched with a repair mortar, cracks (greater than 10 mils) should be epoxy injected, and corroding reinforcing steel should be cleaned. Surface dust, oil, and laitance should be removed; and abrasive blasting, grinding, or water blasting should be used to open the pore structure of the concrete. Once the surface is prepared, a primer coat of resin is applied to the surface with a roller and any small voids or bug holes are filled with putty.

The actual FRP system is installed by sandwiching the dry fiber sheet between two layers of resin (i.e., total fiber impregnation). The first resin or saturant coat is applied to the primed surface using a roller and the fiber sheet is gently pressed into the saturant. The saturant is sufficient to hold the fiber in place even in overhead applications. The system in this state is allowed to set several minutes so that the saturant may be absorbed into the fiber. After approximately 30 minutes, a second coat of saturant is applied to complete the formation of the FRP material. In many applications, more than one ply of the fiber sheet is required to achieve the necessary strength. In these situations, another coat of saturant must be applied (in addition to the second coat used for the first ply of fiber) followed by the fiber and a second coat of saturant.

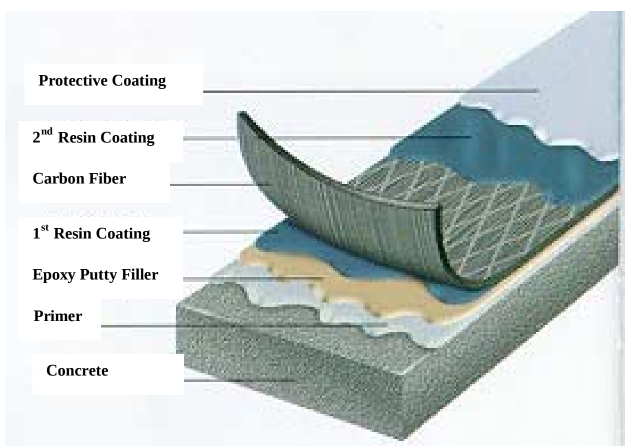


Figure 2: Installation procedure of FRP sheet system

After the saturant has cured and is tack free (this takes several hours and is dependent on environmental conditions), a final topcoat may be applied. Various topcoats are available that provide protection from UV exposure, protection from abrasion, enhanced fire performance, or simply as an aesthetic coat to match the appearance of the original substrate.

## Quality Control

Quality control is crucial to the success of these systems. The quality control process starts before any material is ever installed, continues through the installation, and may sometimes include load testing of the strengthened structure.

The process starts by first determining if FRP is the right solution. The Master Builders MBrace system utilizes an engineering group to review each strengthening application and assess the feasibility of using FRP. Variables like the substrate strength, load levels, operating environments, etc. are evaluated in this review. In some instances FRP will not work and a traditional alternate is recommended. Using FRP in the wrong application is like "hammering a square peg into a round hole".

Once it has been determined that FRP is a good solution and an engineering design has been completed it is time to select materials. Materials selection is very important to quality. Only systems based on extensive testing should be specified. Combining fibers with resins in an arbitrary fashion can yield unpredictable properties and potential material incompatibilities.

FRP strengthening systems are deceptively simple to install. Proper installation is not difficult, however improper installation by not properly saturating the fibers, misaligning the fibers, etc. is not easily avoided without careful attention. Since this material is a structural component, it is absolutely critical that each application be done correctly. Master Builders uses a network of trained and certified contractors to install the MBrace system. Structural Preservation Systems, Inc. serves as the Master Contractor and provides training for select contractors worldwide. This type of training is critical to the success of an FRP strengthening system.

Once an FRP system is installed, verifying the quality of the installation is typically accomplished using two techniques. Hammer sounding or tap testing is used to find delaminations between the FRP and the substrate. Most systems permit a limited number of small delaminations without compromising their strength. Larger delaminations should either be injected with resin or repaired. The pull-off test is used to verify the bond to the substrate and the level of saturation in some systems. A small steel plate (1½"x1½" or 2"x2") is bonded to the cured system and pulled with a testing apparatus. The force required to pull-off the plate is measured and the failure mode is observed. A minimum value of 200 psi and bulk concrete failure is required to insure that the substrate surface was prepared properly.

For some strengthening projects a final quality control step is performed by implementing a load test. After completing the FRP installation the structure is loaded and monitored to verify that the FRP strengthened structure is behaving per design. Techniques developed in Europe that use hydraulic jacks make these types of load tests very rapid and cost effective. This technique has been successfully applied to verify the performance of FRP strengthened systems in many project (Nanni and Gold 1998). One example of complete system performance verification is the ongoing testing to failure of strengthened bridge in Missouri. Two of the three RC solid slabs of the bridge were strengthened with externally bonded FRP sheets and near-surface mounted FRP rods, respectively. Bridge piers were strengthened using near surface mounted FRP rods and FRP sheet wrapping. The objectives of this project include the verification of the effectiveness of different strengthening techniques, determination of the effect of FRP systems on the elastic response of the strengthened structure, and evaluation of the modes of failure of the structural components with and without strengthening.

Figure 3: Bridge after column and deck strengthening

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