Strong Medicine

Fiber-reinforced polymer materials can help cure many ills that beset concrete

By George W. Hoff

Inadequate design and construction, reinforcing-steel corrosion, change of use, and deterioration due to a variety of environmental effects all create a need for structural strengthening of concrete. Historically this strengthening has been done by conventional means, such as section enlargement, external post-tensioning, and steel-plate bonding. However, more and more engineers are turning to fiber-reinforced polymer (FRP) materials for concrete strengthening, repair, and retrofitting.

Three forms of FRP systems are currently in use for concrete strengthening: fabric sheets, pultruded strips, and prefabricated elements. One or more layers of FRP fabric or prefabricated FRP elements can be wrapped around or placed over weakened concrete members onto which an adhesive has been troweled or sprayed to bond the FRP in place. This forms an external strengthener that helps support loads and prevents excessive deflections. In addition to rapid installation, FRP materials offer the advantages of superior strength and stiffness-to-weight ratios and a high degree of chemical inertness in most environments.

Jay Thomas, vice president of the strengthening division of Structural Preservation Systems Inc., Baltimore, a provider of sheet FRP systems, says that a few key factors are causing owners and the engineering community to move to mainstream acceptance of FRP systems. First is a growing history of successful FRP jobs, which will exceed 500 this year. Second is design support. Design guidelines (from both the manufacturers and the American Concrete Institute) and Internet-accessible design programs are now available. "And the cost of FRP is falling due to U.S. manufacture and increased volumes of materials," says Thomas. "FRP is very cost competitive vs. conventional strengthening systems."

Sika Corp.

Sheet lay-up FRP systems are used to improve column confinement in a seismic-retrofit project (above) and to strengthen bridge girders (right).

David White, marketing manager for Sika Corp., Lyndhurst, N.J., which produces pultruded strips and sheets, says that FRPs offer advantages to all the players in the project cycle. "Owners like the versatility of the system and the ability to make modifications to buildings. Engineers are intrigued by the tremendous strength-to-weight ratio and the noncorrodible nature of the material. Con-tractors love the ease of handling and the ability to upgrade structures in a timely manner."

Substrate preparation

None of the FRP strengthening systems will work unless the FRP has a sound bond to a sound substrate. The skin of the concrete can be the weakest link in the strengthening process, particularly in severe environments. Although workmanship and quality control of surface repair are the two most important factors determining the strength and durability of the bond, other factors include:

- Tensile strength of the concrete skin
- Uniformity and thickness of the adhesive layer
- Strength of the epoxy adhesion system
- Geometry of the element being strengthened
- Environmental conditions at application and curing

Before installing an FRP system, prepare the concrete substrate by treating cracks, spalls, and corroding reinforcing steel. Spalls and other surface voids require patching with suitable repair mortars, and all cracks greater than 0.01 inch wide and subject to movement from temperature changes, vibration, or other sources should be epoxy injected. Corroding reinforcing steel should be cleaned or replaced since FRP systems aren't designed to resist the large expansive forces generated by continuing reinforcing-steel corrosion.

Also remove laitance, dust, dirt, oil, curing compounds, and any other loose and unsound materials on the concrete surface. Mechanical abrasion methods, such as abrasive blasting, grinding, or water blasting, remove the contaminants while opening the pore structure of the concrete prior to FRP application.

Isis Canada

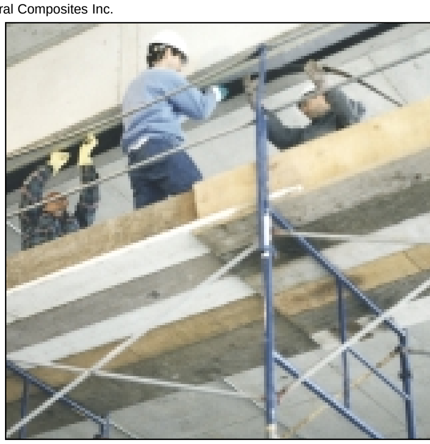
FRP sheets

Both carbon and E-glass FRP systems are available in sheet form. For concrete strengthening applications, the most common carbon-fiber products come in 20-inch-wide rolls of continuous fiber lightly adhered to a paper backing. However, wider rolls or narrower 1/4-inch-wide tape can be provided for special applications. Carbon fibers in the rolls can be aligned in only one direction or oriented in more than one direction by weaving the carbon tows. The latter is usually used for shear strengthening applications.

Once the substrate surface is prepared, apply an epoxy primer coat using a short- or medium-nap roller. Typically, the primer epoxy is of low viscosity (400 centipoises at 77° F), allowing it to penetrate the concrete. Next, trowel apply an epoxy putty or paste (typically 45,000 centipoises at 77° F) to fill any surface defects up to 1/4 inch deep. (Deeper holes or large areas of damage should have been chipped out and repaired with mortar during surface preparation.) Complete coverage is normally not necessary, and the putty or paste can be applied to the freshly primed surface without waiting for the primer to cure.

Next, coat the substrate with a saturant epoxy (usually 1,350 centipoises at 77° F) to impregnate the dry fibers and maintain them in their intended orientation. Typical-ly applied with a medium-nap roller, the saturant is formulated to quickly wet the fibers and hold the fiber tow in

Structural Composites Inc.



Sika Corp.

Workers apply pultruded strips to strengthen the negative-moment region of an industrial floor (above) and the post-tensioned beams of a parking garage (left).

place as the epoxy cures. The saturant also distributes stress to the fibers and helps to protect them from abrasion and environmental degradation. Though FRP sheets pre-impregnated with epoxy are available, they are best suited for use in controlled environments, such as enclosed precast-concrete plants.

Measure and cut the FRP sheets prior to installation. Then, leaving the backing paper in place, put the sheet on the concrete surface and gently press it into the saturant, using a squeegee or trowel to remove any air bubbles. After removing the backing paper, roll a ribbed roller in the direction of the fibers to facilitate impregnation by separating the fibers. Never use the roller in a direction transverse to fiber orientation because it could damage the fibers. The saturant epoxy typically is colored and should be visible on the fiber sheet after rolling.

Wait 30 minutes after rolling the sheet to allow absorption of the first saturant coat, then use a medium-nap roller to apply a second coat of saturant. For carbon-fiber sheets, apply this coat to a thickness of 15 to 20 mils. More saturant is required for E-glass sheets because they're thicker.

If additional plies of fiber sheet are to be added, the surface can be resaturated 30 minutes after the second saturant coat is applied and the sheet installation procedures can be repeated. As many plies as necessary can be installed in this manner.

Once the applied material has become tack-free, a finish coat can be applied. Products are available that mimic the color of concrete and offer protection from ultraviolet light, chemical splash, abrasion, environmental exposures, and fire.

Pultruded strips

Pultruded strips made of carbon, E-glass, or alkaline-resistant (AR) glass filaments are manufactured by pulling the filaments through an epoxy-impregnated bath, then using heat to produce hardened strips with all the filaments aligned along the longitudinal axis. Strips can be of any length up to 820 feet, in widths of 2 to 6 inches and typical thicknesses of 0.047 to 0.059 inch. The tensile strength of a typical strip is reported to be 406,000 psi with an elongation at break of 1.9%.

The strips usually are delivered to the jobsite coiled in a box. The contractor has the option of receiving custom cut lengths or one continuous length to be cut on the job, with tools such as guillotine or heavy-duty shears.

Before strip installation, wipe strip surfaces clean using an appropriate cleaner. For carbon-fiber strips, use a clean, white cloth to apply acetone on the side of the strip that isn't labeled. Continue wiping until all residual carbon dust is removed. When the concrete strengthening design requires stacking of the strips, lightly sand the bottom of the strip (which is labeled) before applying the second strip.

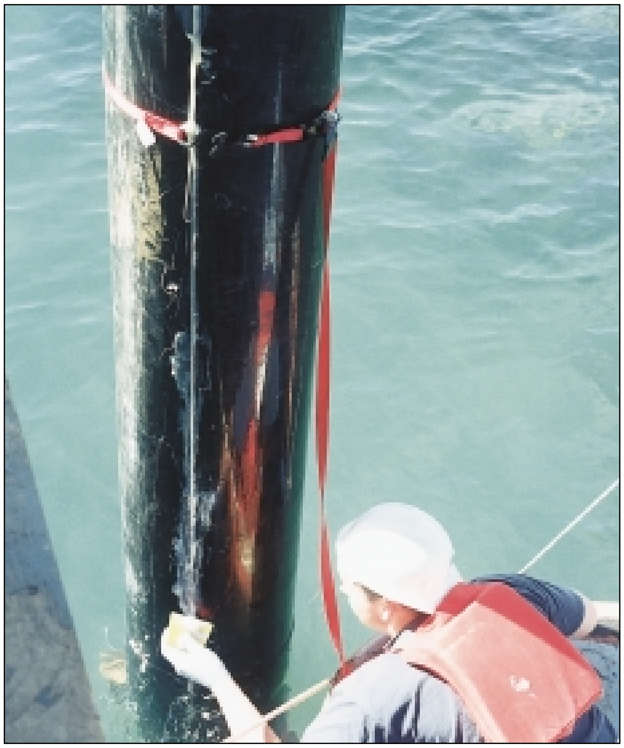
Strip suppliers recommend using a two-component epoxy to bond the strip to the substrate. First apply a 1/16-inch-thick prime coat to the substrate with a spatula, making the application about 1/2 inch wider than the strip to be used. Next, use a spatula to apply the same epoxy to the unlabelled side of the strip at a nominal thickness of 1/16 inch. A preferred method of doing this is to fabricate a hopper for the epoxy. Holding the spatula at one end, pull the strip through the hopper, under the epoxy, and then past the spatula to produce a uniform cross section.

When both the strip and the substrate have been coated with epoxy, place the strip on the concrete (epoxy to epoxy), using a rubber roller to properly seat the strip. Apply enough pressure to force the epoxy out at both sides of the strip and to produce a maximum glue-line thickness of 1/8 inch before carefully removing excess epoxy. Care should be taken not to disturb the material for at least 24 hours. The strip should reach design strength in 7 days.

Prefabricated components

FRP composites also are available as prefabricated components that can be placed around or on structural elements to strengthen them. A variety of structural shapes can be produced to meet specific project requirements. The most common prefabricated components are circular shells, L-shaped elements, and flat plates.

The components are made using E-glass, carbon, or aramid fibers or a combination of those fiber types. The fibers are formed into a knit fabric that's typically solidified by an epoxy vinyl ester. Ultraviolet radiation inhibitors often are added to the epoxy vinyl ester to extend the service life of the product. A common method of fabrication uses a high-production, vacuum-assisted molding process that produces high-performance composite



Hardcore Composites

Prefabricated shells are ideally suited for strengthening structural elements, such as this marine pier column partially submerged in water (top photo). To repair columns for a bridge overpass on the New Jersey Turnpike, a contractor installed composite jackets at a rate of eight per day (bottom).

parts with a low void content and high fiber volume. The fibers can be unidirectionally oriented (mostly for seismic-retrofit applications) or have multi-axis orientation (for structural strengthening, containment and protection, and impact and blast resistance). Because the elements are made in a quality-controlled factory environment, precise shape, controlled fiber orientation, increased fiber volumes (for enhanced strength), and optimum surface finishes can be achieved.

For seismic retrofit of circular columns and piers 12 to 72 inches in diameter, three overlapping FRP shells are typically used. The inner two shells are not a complete 360-degree circle but are made with a portion (about a 60-degree arc) of the shell omitted. A full 360-degree outer shell encloses the inner shells.

Place the first shell on the existing column to verify length, then remove and trim it to the optimal length before making similar checks for the other two shells. Once the proper dimensions are achieved, lightly sand the interior surface of the first inner shell and apply a 3- to 5-mil-thick layer of epoxy before placing the shell back on the column. Next, sand and apply epoxy to an identical shell, positioning it to cover the opening in the first shell. Repeat the procedure once more, completely enclosing the column with the 360-degree shell. Attach and tighten ratchet straps at several locations on the outer surface to squeeze all the shells together, then remove excess epoxy at the outer-shell joint to give a smooth surface appearance. Remove the straps after the epoxy has cured (typically after 8 hours).

For seismic retrofit of rectangular or square columns and piers, use L-shaped FRP elements, preparing them for installation in the same manner used for the circular shells. The length of each leg of the L is approximately the dimension of the column face to which it will be applied. Each corner of the column fits into a corner of an L so that the resulting cross section has two layers of composite FRP on each face. Use of FRP composite shells and elements has been approved by Caltrans for seismic-retrofit upgrades.

For structural strengthening, use FRP shells and Ls made with multi-axis fibers. For circular columns, the installation procedure is similar to that used for seismic retrofitting except that only two shells are used. For columns 18 to 72 inches in diameter, the two shells are not a complete 360-degree circle but are made with a portion (about a 120-degree arc) of the shell omitted. The first shell is placed on the column followed by the second shell, which should overlap the first so the gap in the first is approximately at the center of the second, outer shell. For smaller-diameter columns (12 to 18 inches), the two shells are simply split on one side during manufacture or at the jobsite so they can be opened to fit around the column. When strengthening square or rectangular columns using the Ls with multi-axis fibers, follow the same procedure used for seismic retrofitting.

For containment and protection, circular shells are used for both circular and square columns. In these instances, the shells are offset from the concrete column or pier, leaving a 2- to 6-inch gap between the column surface and the shell. The offset can accommodate a variety of structural contours and damaged or uneven substrates. The gap is later filled with grout, usually placed by pumping.

For 12- to 18-inch-diameter columns, split the shell on one side and open it to fit around the column. A special H-connector into which the edges of the shell fit is used to close the shell. Place a 3- to 5-mil bead of epoxy in both grooves of the H-connector before inserting the edges of the shell in the grooves. Use ratchet straps at the top and bottom of the shell to squeeze the shell together until the epoxy has cured. For 18- to 72-inch circular columns, use two 180-degree shell pieces and two H-connectors to join the shell edges.

For square and rectangular columns, shells from 12 to 50 inches in diameter are available. They also come in two 180-degree pieces requiring two H-connectors. A minimum clearance of 1 inch from the corner of the column to the inside edge of the shell is recommended.

Another form of prefabricated shell material comes as a coil in which the FRP can either be cut into discrete pieces to form a shell or be continuously wrapped for several layers around a column. The coil is typically 0.1 inch thick and comes in 4 1/2-foot widths if made with E-glass and 2-foot widths if made with carbon fibers. However, the width can be customized to suit the application. In 1998, the coil-type prefabricated element was used to seismic retrofit 3,480 concrete columns on the Yolo Causeway in Northern California. A crew of six completed the job in only 3 months.

Prefabricated FRP elements in the form of flat plates and other geometries can also be made for specific applications. These typically are made with multi-axis fibers and fastened to the structure with epoxy.

According to Mark Ewen, business director for Hardcore Composites, Newcastle, Del., "The longevity and strength performance of piers and piles can be greatly improved with prefabricated FRP shells. They don't require special equipment or special job skills. Because traditional methods of strengthening or retrofitting columns, piles, and piers are unworkable in water, the use of prefabricated structural shells provides a quick, easy, and cost-effective solution." ■

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