Evolution of FRP Products for Concrete Repair

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Introduction

Nearly four decades ago, the author introduced the use of non-metallic Fiber Reinforced Polymer (FRP) products for repair and strengthening of deteriorated beams (Saadatmanesh and Ehsani 1988, 1990). In that original concept, known as the wet layup technique, fabrics made with glass or carbon fibers are saturated with epoxy in the field and applied to the exterior surface of the concrete. By the next day, when the epoxy cures, the FRP reaches a tensile strength 2-3 times that of steel. That system has been used on thousands of projects worldwide and several countries have developed design guidelines for such repairs. In a typical design, the FRP is used to supplement the reduction in capacity of the structural element that occurs when the steel area is reduced by corrosion.

There are a few major shortcomings with the wet layup system. The first problem is that the fabric must be directly bonded to a concave surface. This limitation means that a corroded steel H-pile, for example, could not benefit from repair with FRP; forcing the fabric to follow the sharp corners of the H pile will also damage the fibers in the fabric. The second limitation is that the surface must be smooth. When a concrete beam or slab is damaged by corrosion, for example, the damaged area must first be patched and flattened with concrete and allowed to dry before the FRP fabric can be applied. This adds significant cost and time to the project. The third shortcoming is that the fabrics cannot be easily applied underwater unless costly cofferdams are constructed.

To overcome the above shortcomings, the author developed the second generation of FRP products dubbed SuperLaminates; that product was introduced on the 20th anniversary of the first paper in *Concrete International* (Ehsani 2010). These laminates are made by saturating a roll of carbon or glass fabric with resin and subjecting it to heat and pressure using special equipment. The result is a thin laminate with a thickness of about 0.04 in. (1mm). The main advantage of these laminates is that they eliminate the need for virtually all surface preparation, saving significant time and money. They can also be applied underwater to repair submerged piles.

The steps for repair of a typical column are shown in Fig. 1. Note that the damaged surface in Fig. 1a does not have to be patched. Plastic spacers shown in Fig. 1b are passed through a zip tie and attached to the column. Longitudinal bars can snap into these spacers. The 4-ft wide laminate is cut in a length equal to twice the perimeter of the shell being wrapped plus 8 in. (200mm). The second half of this laminate is coated with an epoxy paste and wrapped around the column and spacers to create a 4-ft tall two-ply shell around the column (Fig. 1c). Additional 4-ft tall shells are similarly installed, overlapping the previous shell by 4 in. (100mm) (Fig. 1d). The annular space between the shells and the host concrete is filled with concrete or grout (Fig. 1e). The finished repaired column is shown in Fig. 1f.

The two-ply laminate shell provides significant confinement for the column, equivalent to #4 ties at a spacing of 2.8 in. (or 12mm bars at 70mm). The elimination of steel ties makes the repair much easier since only longitudinal bars must be inserted into the spacers. Note that the impervious shell will prevent any moisture or oxygen ingress, drastically reducing the corrosion rate in the column for decades.

These laminates are also ideal for repair of submerged piles without the need for any cofferdam. The product has been tested extensively by the US Army Corps of Engineers and it is the only system that the US military uses worldwide to repair deteriorated piles (USACE 2018). Thousands of piles have been repaired with this system globally for various ports and other clients since its introduction in 2012.

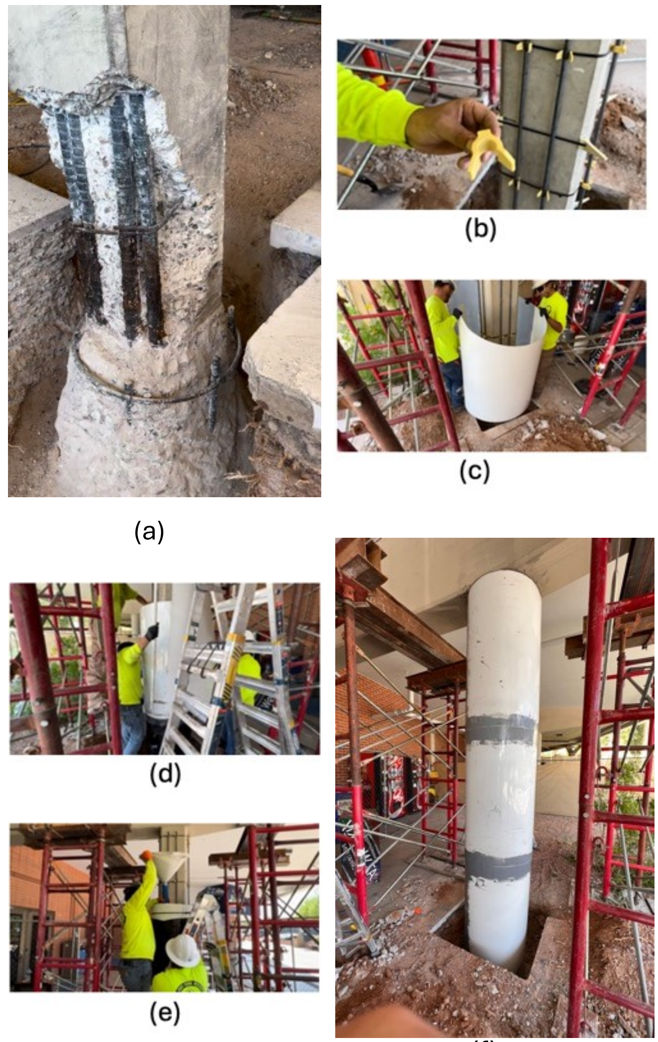


Fig. 1. Repair of a deteriorated column with FRP laminate; (a) damaged surface; (b) installing the spacers and rebars; (c) wrapping the first laminate to create a shell; (d) wrapping additional laminates; (e) filling the annular space; and (f) completed repair.

The Third Generation of FRP

This paper introduces the latest FRP product developed by the author that can revolutionize the concrete repair industry. This unique product can single handedly replace three products commonly used on many repair projects, namely: a) formwork, b) reinforcing steel, and c) waterproofing.

The patent-pending panels, named SPiRe®+, will be hereafter referred to as T-panels. The panels are 3-ft (910mm) wide and can be cut to any length in the field (Fig. 2a). They are constructed with glass fabric using a pultrusion process. The exterior face of the panels is flat and smooth. The interior face has protruding T profiles. That face is also grit coated for improved bonding to concrete. Together, the flat panel and the T profiles act as reinforcing elements for strengthening any beam, slab or wall (Fig. 2b). The panel wall thickness is 0.2 in. (5mm).

(a) (b)

Fig. 2. T-panels: (a) 3-ft wide x 12 or 18-ft long; (b) close view of grit coated surface and equivalency to steel reinforcing bars.

For repair of walls or slabs, the edges of the panels are overlapped by 4 in. (100mm). A sealant is applied on this overlapping region in the field to create an impervious watertight joint. In a typical repair project, the panels are secured to the corroded structure with anchor bolts to create the desired annular space of 2 in. (50 mm) or larger. This annular space is subsequently filled with cementitious or epoxy grout to bond the panels to the host structure. A main advantage of the system is that it requires virtually no surface preparation. In fact, the rougher the surface of the host structure, the better the bond between the panels and newly placed grout and the host structure.

Flexural Test

The strength of the T-panels can be demonstrated with the test shown below. An 8-in. (200mm) wide piece of this panel was used to build a beam with a height of 4 in. (100mm) and length of 9 ft (2.74 m) (Fig. 3a). A non-shrink precision grout by Quikrete was used. Per manufacturer's recommendation, 5 ¼ quarts of water was mixed with each 50 pound bag (5 L per 22.6 kg bag); this would produce a grout with a consistency between flowable

(a) (b) (c)

Fig. 3. Test specimen; (a) formwork; (b) mixing and placement of grout; and (c) flexural testing of the beam.

and fluid (Fig. 3b). The beam was subjected to a 4-point bending and the load vs. midspan deflection results are shown in Fig. 4.

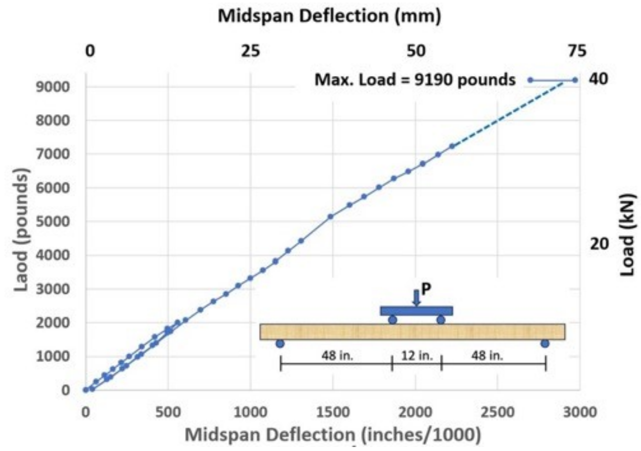


Fig. 4. Load vs. midspan deflection of the beam constructed with T-panel

The only reinforcement in the beam specimen was provided by the two T profiles and the flat plate of the T-panel (Fig. 3c). A large number of fine flexural cracks formed along the length of the beam, indicating good bond between the T-panel and the concrete due to the grit-coated surface. The specimen failed at a load of 9190 pounds (41 kN); which corresponds to a flexural moment of 220.5 k-in. (24.9 kNm). In comparison, if this 4-in. (100mm) thick beam were constructed with steel reinforcement, it would require #6 Grade 60 steel bars at a spacing of 3 ½ in. (or 20mm ø, 500MPa @120mm) to provide the same flexural capacity. Fig 2b shows this equivalent steel area; it is evident that the strength provided by these panels exceeds the reinforcement required for most projects.

Applications

The uses of this new product are practically limited by one's imagination. The immediate adoption of this technology for so many repair projects attests to the value and unique benefits that these panels offer.

Repair of Seawalls - Some of the early adopters have been projects for repair of seawalls where these panels offer significant advantages by eliminating the need for cofferdams. Figure 5 shows a deteriorated timbe seawall in [Anable Basin](), Queens NY that was repaired. The rotting timber caused soil loss, jeopardizing the safety of the wall and the

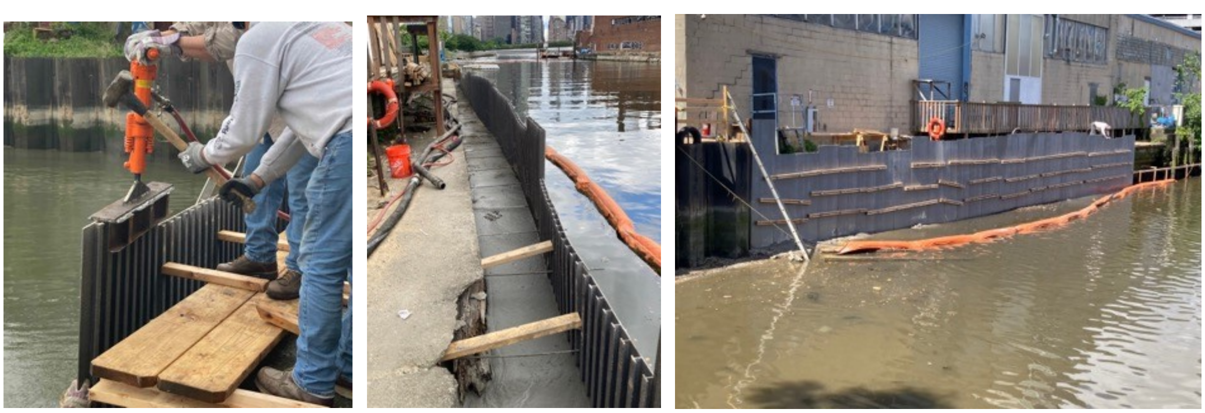


Fig. 5. Deteriorated timber seawall in Anable Basin, Queens NY repaired with T-panels in July 2024: (a) installing the panels by vibration, (b) grouting behind the panels, and (c) trimming the top of the panels to a uniform elevation.

nearby structures. The panels were anchored to the wall with a specially designed and constructed long tap-lag bolts. The annular space was filled with a flowable fill (Fig. 5b) and the top edge of the panels was trimmed flush.

A similar application for repair of a severely corroded steel seawall is currently in progress in the city of Weston, FL (Fig. 6). These are parts of two pump stations where excess flood water is pumped from a retention pond into a canal. In some cases, the holes in the walls were as large as 1 square foot (0.1 m^2) which would allow significant loss of soil through the wall. In a few areas the walls were surrounded by water on both sides. These were sandwiched between two sets of T-panels, one on each side of the wall. Another

Fig. 6. Repair of corroded steel sheet piles in Weston, FL, June 2024

Fig. 7. Concrete pier wall in a bridge in North Dakota scheduled to be repaired in August 2024.

major project that was recently awarded is to repair 1800 ft (549 m) of an 18-ft (5.5 m) tall seawall at a submarine repair facility at General Dynamics in Groton, CT. Construction on that project is scheduled to begin in late 2024.

Repair of Bridge Pier Walls – Pier walls in river crossings often get damaged by abrasion, erosion and corrosion. Repairing concrete below waterline is a challenging task. In its first application of this type, T-panels are being used to repair the pier wall shown in Fig. 7 in Buffalo Creek Bridge in North Dakota. The panels will be connected by anchor bolts to the wall from the riverbed to an elevation 9 feet (2.74 m) above the mudline. These panels will cover both sides and the front and rear ends of the wall, creating a watertight form that will be filled with concrete. The panels will serve as formwork and reinforcing bars and will provide waterproofing for the repaired wall.

Repair of Beams and Slabs - Corrosion of reinforcing bars in slabs and girders in buildings, bridges and ports results in loss of load-carrying capacity in these structures. Repairs can be very time consuming with significant effort required to prepare the surface and patch it by troweling concrete or spraying shotcrete. In some structures, such as bridges, these long repair times cause delays in traffic and road closures. As shown in Fig. 8, these panels can be cut and connected using L-shaped angles along the corners

Fig. 8. Concrete beams and slabs can be repaired in a few hours with T-panels

to create a shell of desired shape and size. If necessary, additional non-corroding GFRP bars can also be added to these panels through the special spacers shown in the drawing. These panels can be lifted in place and secured with bolts to the host structure before concrete is pumped into the annular space through provided grout ports. Such repairs can be completed in hours instead of weeks, saving significant time and cost for the project. The panels serve as the formwork, reinforcing bars and provide permanent protection for the host structure against moisture, salt spray, and corrosion.

Similar conditions exist in mines and industrial plants as shown in Fig. 9. The slab in this plant was severely corroded due to the presence of chemicals and fumes in the plant. Access to the underside of the slab at such height and at the presence of existing pipes and attachments is very limited, making conventional repairs with patching of concrete impractical. The SPiRe®+ panels can be lifted from below and secured with a few bolts to the underside of the slab. The annular space is filled with grout or concrete.

Fig. 9. Severely corroded slab in an industrial plant

As part of the design for such applications, a check must be made to ensure proper transfer of loads from the T-panels to the host structure through shear. Rough concrete surfaces do provide a large degree of shear transfer. If necessary, anchor bolts can be designed to connect the panels to the host structure and provide additional shear transfer capacity.

Construction of Retaining Walls - The panels can be used to build retaining walls. As shown in the detail in Fig. 10, the footing can be cast, and 2-ft (600mm) long starter bars will extend above the footing. Two rows of T-panels are placed above the footing facing each other at the required distance for the wall thickness; these are connected with through bolts at desired locations. The annular space is filled with concrete. The starter bar extensions provide the adequate overlap length to engage the T profiles which are the primary reinforcing element in the wall. The overlapping edge of the panels are sealed with a sealant to provide a watertight panel. This eliminates the need for waterproofing, which is a costly component of retaining walls. So, the panels serve as formwork, reinforcing bars, and provide waterproofing for the wall.

Rising Sea Level – Global warming and climate changes have resulted in flooding and surges in coastal and riverfront communities. The existing seawalls are often short and must be extended to higher elevations. Some communities have passed regulations requiring that this issue be addressed by a certain deadline. T-panels can be securely connected to the top edge of the existing seawall cap (Fig. 11a). Additional panels will be placed on the opposite side and these panels will be bolted together. The annular space between these panels is filled with concrete (Fig. 11b). This creates a wall that in most cases requires no steel reinforcing bars. Thus, the non-corroding wall will last virtually forever! If desired, the land side can be enhanced by providing planters, benches, walkways, etc. (Fig. 11c). Click to watch a video of this system called [ESeaWall](). A couple of projects using this technique are under design for sites in Miami FL with construction expected to begin in 2025.

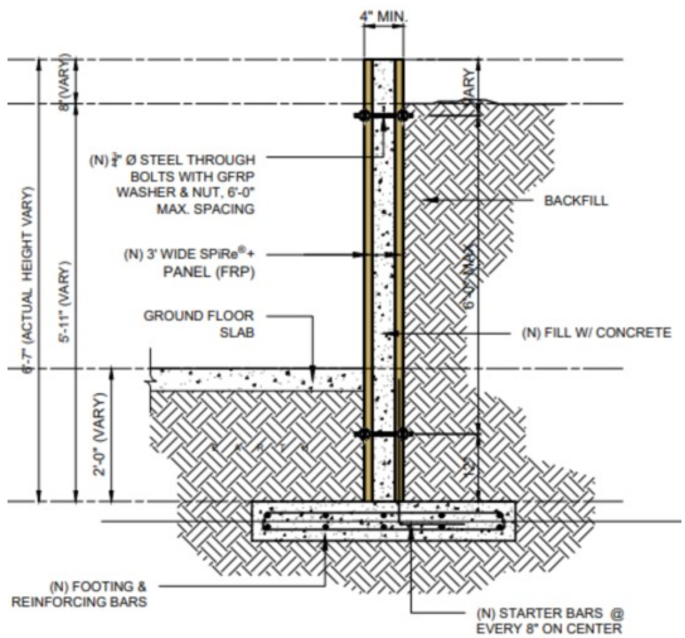
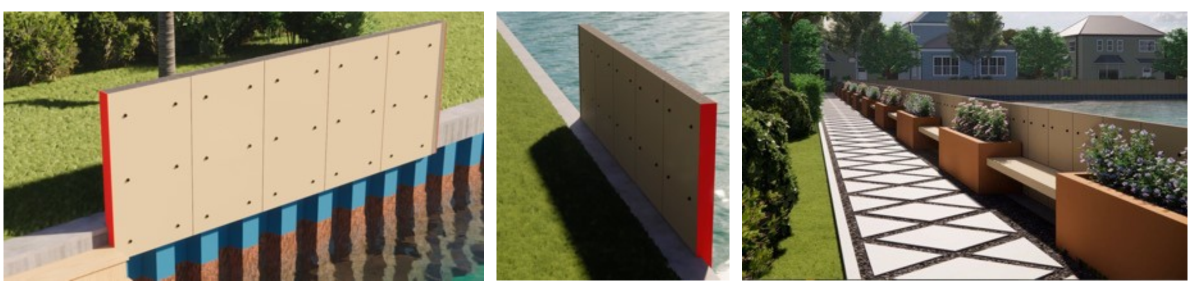


Fig. 10. Construction of retaining walls with T-panels



(a) (b) (c)

Fig. 11. Extension of the height of seawalls in response to flooding caused by rising sea levels; (a) attach SPiRe®+ panels to edge of seawall, (b) connect panels on the opposite face and fill annular space with concrete, and (c) optional planters and walkways on the land side.

Summary

The evolution of FRP products for concrete repair over four decades has led to the development of a new type of FRP panel. These panels have built in grit-coated T profiles that bond to concrete and serve as reinforcing elements for the concrete. In repair application, the panels can be bolted to the existing structure and the annular space between the structure and the panels is filled with concrete. As such, the panels serve 3 functions: formwork, non-corroding reinforcing bars, and waterproofing. The wide range of applications presented here for repair of seawalls, bridge pier walls, beams and slabs, retaining walls and addressing flooding in coastal communities attest to the unique features of this product. Not only the panel itself is made of non-corroding FRP, but it also serves as a thick moisture barrier, protecting the host structure from future corrosion for decades.

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