

FRP Super Laminates

Transforming the Future of Repair and Retrofit with FRP

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Nearly two decades have gone by since the author presented his novel idea for strengthening of concrete beams with external bonding of Fiber Reinforced Polymer (FRP) laminates in an ACI publication (Saadatmanesh and Ehsani, 1990). In the aftermath of the 1989 Loma Prieta earthquake, the author proposed an extension of his earlier research to retrofit deficient bridge piers by lateral confinement with FRP (Engineering News Record, 1990). What appeared to be unusual approaches at the time have since become mainstream techniques for repair and retrofit of structures worldwide. The ACI Committee 440 that was formed in the following years enjoys the largest membership among ACI Committees, a testimony to the global interest in FRP.

The high tensile strength, light weight, durability and versatility of FRPs have made these products the material of choice for many repair and rehabilitation projects. To date, numerous bridges, buildings, pipelines, etc. have been retrofitted with these products worldwide. With the publication of design guidelines (ACI 440-08) it is fair to say that FRP is no longer an experimental product but rather a relatively well-accepted construction material.

The forms of FRP products that have been used in retrofit applications to date can be categorized into fabrics and pre-cured laminates. Fabrics offer the widest versatility in the field and are installed with what is commonly referred to as the wet layup method. This technique requires properly trained technicians to prepare the resin in the field, saturate the fabric and apply it to the structural member. Care must be taken to ensure the fibers are aligned in proper directions and to remove all air bubbles before the fabric is cured.

Pre-cured laminates allow easier field installation because the saturation of fibers mentioned above is carried out in a plant. They are available in the shape of reinforcing rods or tendons as well as narrow unidirectional laminate strips that are typically produced in the range of 3-4 inches (75 – 100 mm) wide and 0.05 inches (1.3 mm) thick. In the field, these laminate strips are bonded to the exterior surface of the structural element using epoxy putty. A variation of this approach known as Near Surface Mounted (NSM) embeds the laminate strips or rods into narrow grooves that are cut in the structural member.

While the laminate strips offer ease of installation and higher strength than the wet layup system, their use has been relatively limited for the following three reasons: a) the unidirectional reinforcement in these laminates makes them primarily suitable only for flexural reinforcement of beams and slabs, with some applications for shear strengthening of beams, b) the stiffness of the laminates does not allow them to be coiled into a circle smaller than approximately 30 inches (750 mm) in diameter, and c) their relatively narrow width is a hindrance in many applications.

The current equipment and technique used to manufacture these laminate strips does not lend itself to making products that are appreciably different. Even with modification of current equipment, one can only produce unidirectional laminate strips that are no wider than approximately 10 inches (255 mm). The overcoming of the above shortcomings in laminate strips is not a trivial matter. In fact, some contractors tried to use 10 inch (250 mm) wide laminate strips in repair of pipelines and abandoned the idea after unsuccessful attempts (Carr 2009).

This paper discusses the development and many uses of super laminates. As such, it is a landmark advance in the field of FRP since its introduction by the author over two decades ago.

Super Laminates

Super laminates are a frog leap development in FRP products since the introduction of FRP in construction industry some twenty years ago. They overcome the shortcomings of the above-

mentioned laminate strips. As discussed below, these products make possible many applications that have challenged the construction industry for decades. In some case, the solutions have not been possible without the development of super laminates.

Super laminates are constructed with specially-designed equipment. Sheets of carbon or glass fabric up to 60 inches (1.5 m) wide (Fig. 1) are saturated with resin and passed through a press that applies uniform heat and pressure to produce the laminates. Super laminates offer three major advantages over conventional laminate strips:

- 1) By combining unidirectional and/or biaxial fabrics, the laminates offer strength in both longitudinal and transverse directions; this is a tremendous advantage that opens the door to many new applications as discussed later.
- 2) They are much thinner than conventional laminates; with a typical thickness of 0.025 inches (0.66 mm), they can fit into a cylinder with a diameter as small as 8 inches (200 mm).
- 3) The number and design of the layers of fabrics can be adjusted to produce an endless array of products that can significantly save construction time and money.

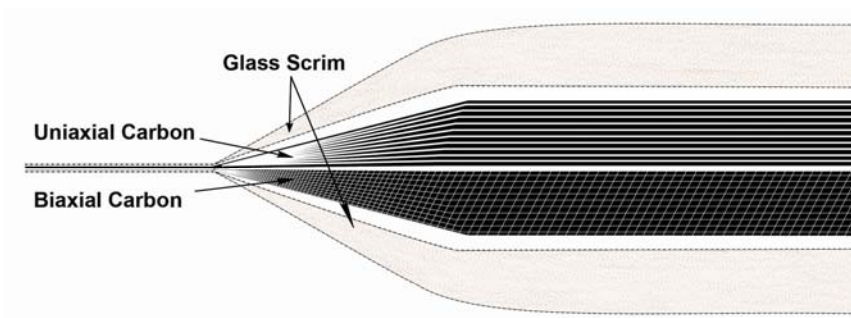


Fig. 1 – Super laminates may be constructed with multiple layers of unidirectional or biaxial fabrics

Figure 2 shows typical super laminates and their flexibility that allows them to be bent by hand. They are produced under ISO-9000 certification that ensures highest standards of quality control. This eliminates much of the reliance that has been placed in the past on the construction crew to produce the FRP in the field using the wet layup system. For example, when the rolls of super laminates are delivered to a construction site, samples can be tested *before* the material is installed. In contrast, in the wet layup application, field-prepared samples are made daily and tested at a later date, at which time repair of defective installations cannot be easily corrected.



Fig. 2 - From left to right: Carbon and glass super laminates; carbon strip

Some of the construction challenges that can be easily addressed with super laminates are described below.

Strengthening of Large-Diameter Pipes

More than 6 billion gallons (23 million liters) of water are lost daily due to leaking pipes (ASCE 2009). Additionally, a large number of pipes in water distribution networks and oil and power industries are badly deteriorated and require repair or strengthening. These pipes are usually pressurized, and deterioration of reinforcement results the hoop stresses to exceed the capacity of the pipe. When unattended, the consequences of such failures are grave and can leave entire neighborhoods under water (Johnson and Shenkiryk 2006) or force emergency shutdown of plants. A common strengthening approach in the last decade has been to apply one or more layers of carbon fabric inside the pipe. The author has been involved in such projects in a major U.S. nuclear power plant since 1988. The fabrics

provide adequate strength in the hoop and longitudinal directions. While very effective, the time associated with the wet layup method has been a major drawback to this system.

Super laminates significantly reduce the construction time. The flexibility of the laminates allows them to be wrapped around cores that are 12 inches (300 mm) in diameter for ease of transport into pipes through manholes that are typically 24 inches (600 mm) in diameter (Fig. 3). The ability of super laminates to conform to the diameter of the pipe, i.e. "one size fits all," is a major time- and money-saving attribute of this system for contractors. Most of the current products on the market that can be used as liners to repair or strengthen pipes have a fixed diameter and cannot be applied to different size pipes.



Fig. 3 – Super laminate being taken into the pipe and installed; one size fits all pipe diameters

Installation involves applying a thin layer of epoxy putty to the back of the super laminate and pressing the laminate against the pipe surface. No effort is required to remove the air bubbles as the super laminates are pre-cured. In fact, depending on the diameter of the pipe, the elastic memory of the coiled super laminate may cause it to expand inside the pipe (like a loaded spring) and snap against the host pipe with little effort. Continuity of the super laminate rings is achieved by adequate overlap lengths in the hoop and longitudinal directions. Thus, unlike ordinary laminates that are unidirectional, super laminates do allow strengthening of the pipe in both hoop and longitudinal directions with a single application.

Not only super laminates are installed faster than fabrics, it is possible to include multiple layers of fabric into a single laminate, further reducing construction time. When steel pipes require strengthening, to avoid galvanic corrosion, a layer of glass fabric is typically applied to the surface of the pipe before any carbon fabric is applied (ACI 440, 2008). This protective layer can also be included in the super laminate, resulting in even further time savings. Thus instead of saturating and applying three layers of fabric to the pipe, the strengthening can be achieved by installing a single layer of super laminate. This can reduce the construction time by as much as 80% in many jobs. Such significant reduction in repair time makes many larger retrofit projects possible, where the water authority, for example, could not afford the long shutdown time required for conventional repairs.

Repair of Small-Diameter Pipes

If the diameter of the pipe is small and human entry is not possible, the pipe can be repaired using a packer. Packers are cylindrical shaped frames that house a closed bladder on the outer surface (Fig. 4). An appropriate length of super laminate can be cut and coated with epoxy putty; the laminate is then wrapped around the packer and is held in that position with the aid of strings. The assembly is lowered into the pipe through access ports and it is pulled to the desired location with the help of closed-circuit TV cameras. The packer is then inflated allowing the super laminate to adhere to the



Fig. 4 -- Flow-through Packer

host pipe; after a few minutes, the packer is deflated and removed from the pipe.

Additional pieces can be similarly installed with a small overlapping length to repair or strengthen a larger length of the pipe.

A major cost associated with pipeline repairs is the traffic control required due to bypass pipes that are laid at the street level. Most repair systems require inserting a flexible pipe or liner between adjacent manholes and curing it using steam or hot water. All such systems require the repair area between the manholes to be clear of any obstacles. Therefore, using plugs at ends, water or sewer is pumped to the ground level to bypass the repair area (Fig. 5a).

In contrast, repairs with super laminates do not have this restriction. Using flow-through packers (Fig. 4), a smaller diameter flexible hose or pipe can be used to bypass the fluids inside the pipe (Fig. 5b). The super laminate can be applied on a third flow-through packer that rides on top of the flexible hose (Fig. 5b) and can deliver the repair materials to the damaged area (Fig. 5c)

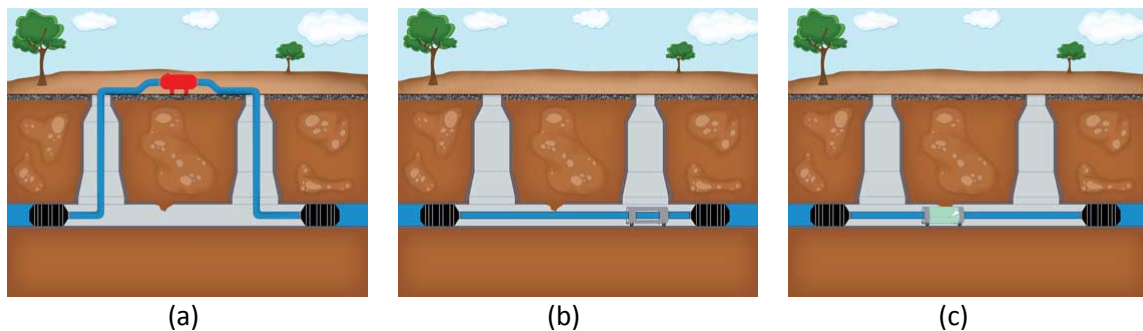


Fig. 5 -- Repair of pipes; (a) conventional method requiring above ground bypass; (b) and (c) using super laminates with bypass through the pipe

Seamless Shell around Existing Columns

A long-standing challenge to the engineering community has been *how to construct a seamless structural shell around an existing column*. One can of course use two half shells and bolt them together in the field to form a shell around the column. But this introduces two limitations: a) the shell has to be custom-made to fit the column size and b) the vertical seams along the sides of the shell introduce planes of weakness which prohibit pressurization of the grout in the annular space.

As depicted in Fig. 6, super laminates make this task very easy. For ease of handling, one may use a narrower super laminate, e.g. 24-inch (600-mm) wide, and start construction of the jacket at the bottom of the column. The overlap is typically one half of the super laminate width, 12 inches (300 mm) in this example. By applying a thin layer of epoxy putty on the overlap portion, the jacket is constructed as the workers approach the top of the column. To prevent the top end of the super laminate from opening (due to its elastic memory), a band of fabric saturated with resin can be wrapped a couple times near the top of the jacket.

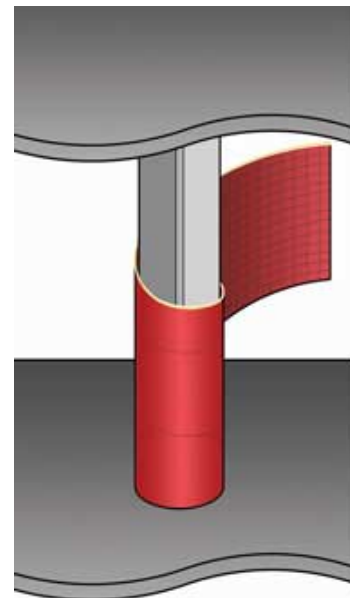


Fig. 6 – Square column being encased in a cylindrical continuous shell made with super laminates

The jacket formed in this manner has no seams along the sides. Based on the design of the super laminate, the end result can be a jacket that has continuous fibers in both hoop and longitudinal axis of the column. The annular space can be filled with expansive grout or resin and, if desired, can be pressurized for improved confinement of the column.

Retrofit of Square Column

It is a well-recognized fact that external confinement of square column sections is not efficient. In these cases, the corners of the column are properly confined but the sides remain relatively unconfined. The challenge has been *how to build a circular FRP jacket around an existing square column*. Of course, one can use temporary forms to cast additional concrete to convert the square column into a circular column, then remove the form and wrap FRP around the circular column. But such an approach is very time-consuming and uneconomical. As shown in Fig. 6, this can be easily achieved using super laminates. A further significant advantage is that a single roll of super laminate can be used to form jackets around many columns of different sizes. This “one size fits all” property results in major savings.

A further advantage of this system is in repair of corrosion damaged columns where the concrete repair can be significantly simpler. At present, once the corroded steel in such columns has been repaired, the column must be coated with concrete to bring it back to its original shape before it can be wrapped with FRP fabrics. Super laminate will eliminate this step as the column jacket can be wrapped around the column with an uneven surface and the result will be a smooth cylindrical shell; the annular space can be filled as discussed above. A similar approach can in fact be used on existing circular columns that are deteriorated due to corrosion

Repair of Underwater Piles

There is a large inventory of bridges, piers and off-shore platforms worldwide that are supported on piles. The splash zone of these piles is subjected to dry-wet cycles that results in rapid deterioration of these elements. Over the years, various systems have been developed to repair such elements. All of these systems require two half shells, typically made of fiber glass and customized to fit the specific pile size. The jackets are pre-manufactured and shipped to the jobsite in bulky crates. In the field, the jackets are placed around the pile and fastened together with steel bolts or straps. The annular space is then filled with grout and the shell is either removed or left in place.

There are three major shortcomings with these systems. First, these installations require advance scheduling and ordering of “custom fit” jackets. Secondly, they require significant time by divers to assist with the underwater installation. Lastly, the presence of vertical seam(s) along the height of the jacket introduces planes of weaknesses that prevent the grout to be pressurized. While the later leads to inferior structural performance, the first two attributes of these systems lead to significantly higher construction costs.



Fig. 7 – Retrofit of underwater piles; from left to right: construction of a seamless jacket with super laminates; filling the annular space; completed pile jacket

Similar to the methods described above for columns, a “seamless” jacket can be made in the field around the existing pile (Fig. 7). A single roll of super laminate can be used for a wide range of pile sizes and shapes, producing a cylindrical jacket around the pile. When field conditions permit, the jacket can be started above waterline (on the dry portions of the pile). Once a couple of turns are completed, the finished portion of the jacket can be gradually lowered into the water, while workers complete the

remaining portion of the jacket above waterline. Moisture-insensitive epoxy putties are available that can be applied and are cured in water. This will greatly facilitate the construction of pile jackets in marine environments and will significantly reduce the need for costly divers.

Once completed, the ends of the annular space between jacket and pile are sealed, for example with a rubber bladder similar to a bicycle tube. Sealing of the lower part of the annular space is the primary task that may require assistance from divers. Then the annular space is filled, and if required, pressurized. The pressurization of the annular space will ensure that the grout or resin fills all the voids and crevices in the deteriorated pile. The pressurization also causes active lateral confinement of the pile, thereby increasing its axial load-carrying capacity.

Repair of Tanks and Silos

Many structures such as silos and water or oil storage tanks are designed as cylinders. The hydrostatic pressure from the stored grains or liquid produces hoop stresses in the side walls of these structures. The stresses are maximum at the base and gradually reduce along the height of the wall. Corrosion results in reduction in cross sectional area of reinforcement in concrete structures and reduction in wall thickness in steel structures. This compromises the hoop strength in these structures.

Super laminates offer economical solutions for such applications. The sheets that can be as wide as 60 inches (1.5 m), and slightly longer than the circumference of the circular tank can be bonded as rings on the inner surface of these structures (Fig. 8). The laminates will be designed as primarily uniaxial products, to provide significant strength in the hoop direction after installation. Continuity of the rings in the horizontal direction can be achieved by overlapping the ends of the rings. The super laminates used in the lower portions of the wall can be constructed with more layers of reinforcing fabrics; the thickness of the super laminate can be reduced for subsequent layers that are installed farther from the base of the tank or silo. Along the height of the wall, super laminates can be overlapped slightly to prevent any fluids stored in the tank from reaching the host structure.

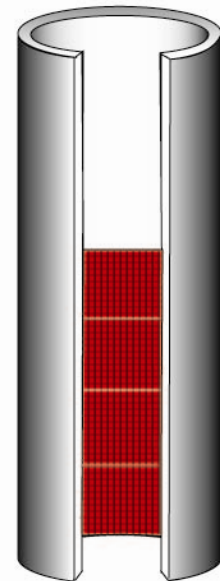


Fig. 8 – Super laminates bonded to the lower portions of tanks and silos

Summary and Conclusions

Following his introduction of FRP products to the construction industry some twenty years, the author presents the development of the next generation of FRP products called super laminates. This product is a major advancement that offers unique solutions to a number of repair and retrofit problems that are not possible with conventional laminates or the wet layup systems that have served the construction industry for the last twenty years. Several applications of super laminates have been detailed in this article. In some cases, these solutions are truly innovative and offer results that have been impossible heretofore.

Super laminates are produced under high quality control conditions and meet ISO-9000 standards. In addition, the products can be tested *prior* to installation, allowing the owner to reject any defective rolls. In contrast, in wet lay-up projects, samples are made in the field and test results will not be known until several days after the installation has been completed. The combination of these attributes should provide more quality assurance for the construction team and will be a catalyst for wider acceptance of FRP products in repair and retrofit projects.

It is hoped that the development of super laminates will further advance the use of FRP products in construction industry for decades to come as the creativity of other researchers leads to new applications for this innovative family of products.

Acknowledgments

The methods of construction and applications of super laminates discussed in this article are protected by several pending U.S. and international patents.

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ACI Fellow, Mo Ehsani has been a Professor of Civil Engineering at the University of Arizona since 1982. In 1994, he founded QuakeWrap, Inc., a company offering turnkey solutions for repair and retrofit of structures with FRP products. Dr. Ehsani has been featured on major media such as CNN, National Public Radio, and the History Channel for his expertise on strengthening of structures, particularly related to earthquakes, terrorist attacks and other potential structural disasters.