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FRP 101: TAKING THE MYSTERY OUT OF TRENCHLESS REPAIR OF PRESSURE PIPES WITH CARBON FRP

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ABSTRACT: Over three decades ago the author introduced the concept of using carbon and glass Fiber Reinforced Polymer (FRP) to the construction industry. In its simplest form, FRP consists of fabrics made with glass or carbon fiber. The fabric is saturated with epoxy resin in the field and applied like wallpaper to the surface of the structure. Within several hours, the epoxy cures and FRP reaches a tensile strength 3-4 times that of steel. While the original applications were on strengthening of beams, columns and walls, the technique has been used extensively in the US. since the late 1990s to repair pressure pipes.

FRP offers a great solution for repair of pipes. Larger diameter pipes can be repaired internally by man entry. For smaller pipes a packer can deliver the materials to the point requiring strengthening. FRP allows restoration of a deteriorated pipe to its original strength. It can also be used to increase the pressure rating of a pipe to levels far beyond the original design capacity.

Unfortunately most engineering programs do not cover this subject and consequently few practicing engineers know how to exploit the unique advantages of this emerging technology. The presentation will focus on introducing the principles of design, advantages and disadvantages of the system, assuring quality control on the job site, etc. Several case studies covering a wide range of host pipe materials (steel, concrete and fiberglass) and for applications to repair water, sewer and oil and gas pipelines will be presented.

1. INTRODUCTION

Corrosion of reinforcing steel in concrete structures is a major cause of the decaying infrastructure worldwide. Billions of dollars are spent annually to repair cracks and spalling concrete in buildings and bridges that are initiated by corrosion of steel. When steel corrodes, its volume increases, and this expansion causes high internal pressures that result in cracking of the concrete surrounding the reinforcing bar. To address this problem, researchers from the University of Arizona began their pioneering studies on the strengthening of structures with externally bonded Fiber Reinforced Polymer (FRP) products in the late 1980s. Prior to that time, carbon fibers were very expensive, and they were used primarily in the aerospace and defense industries. With the end of the Cold War, there was a reduced demand for these products in defense-related applications; this resulted in a significant reduction in cost of carbon fiber such that it could be considered for use in other industries such as construction, sporting goods and the like.

The initial focus of the researchers was to repair corrosion-damaged concrete beams and bridge girders as presented in one of the first papers published in this subject (Ehsani and Saadatmanesh, 1990). Following the

1989 Loma Prieta earthquake, the same researchers proposed an extension of their research to externally wrap columns in bridges with FRP. The author received the first U.S. National Science Foundation funded grants to study retrofit of bridge piers (Saadatmanesh, et al. 1994) and unreinforced masonry walls (Ehsani, et al. 1997) with FRP products. What was considered to be an unusual approach by many skeptics at the time, has since become a recognized technique for repair and retrofit of structures worldwide.

Application of FRP to repair pressure pipelines was introduced in the late 1990s at Paloverde Nuclear Generating Station, the largest nuclear power plant in the U.S. These repairs were performed on large diameter (2.4 – 3.0 m) Prestressed Concrete Cylinder Pipe (PCCP) segments that are a part of the cooling system for the facility. The flurry of global research and development activities in FRP applications has resulted in a number of international conferences on this subject. The American Society of Civil Engineers started publication of Journal of Composites for Construction in 1997. For many rehabilitation projects, the high tensile strength, light weight, durability and versatility of FRPs have made these products the material of choice. Numerous buildings, bridges, pipelines, etc. have been retrofitted with these products worldwide. The American Concrete Institute (ACI) Committee 440 was formed in 1996 and has published several documents culminating with the latest design guidelines (ACI 440.2R-17). The recently published ANSI/AWWA C305-18 Standard provides detailed information on rehabilitation of PCCP with Carbon FRP. It is fair to say that FRP is no longer an experimental product and is rapidly becoming a well-accepted construction material.

2. FRP MATERIALS

FRP systems are essentially comprised of two major components: fabrics and resins (Fig. 1). Carbon and glass are the most common types of fabrics employed; the black fabric in Fig. 1 is carbon and the white fabric is made with glass fibers. Carbon, for example, is provided in tows that consist of thousands of filaments. The more common types for construction industry are 12k and 24k tows, which consist of 12,000 and 24,000 filaments, respectively. A number of fabric manufacturers weave these tows into fabrics of different densities. For pipeline repair, fabrics weighing between 18 to 40 oz/yd^2 (600 to 1350 g/m^2) are common. The fabrics are usually supplied in long rolls and are 24 or 50 inch (610 or 1270 mm) wide.

Fig. 1 – FRP products introduced in the late 1980s: carbon and glass fabrics, carbon laminate strips, and buckets of saturating resin

The most common type of resin used for pipe repair is epoxy, though other types of resins are also common such as vinyl ester. Epoxy resins usually consist of 100% solid two component solutions that are mixed in the field according to a volumetric or weight ratio as prescribed by the manufacturer. Most of the epoxies used are ambient cured and fully cure in less than 24 hours. If necessary, application of heat can expedite the curing process. A handful of producers offer FRP systems that meet the ANSI/NSF Standard 61 for repair of potable water pipes with diameters as small as 8 inches (200 mm).

The technique commonly used to repair large diameter pipes is referred to as wet layup. Another technique developed by the author that utilizes SuperLaminate is described later in this paper. In the wet layup technique, carbon fabrics are saturated with an epoxy in the field. The resin serves two functions. First, it distributes the load among all fibers, so all fibers contribute to the strength of the laminate. Second, it protects the fibers from damage, abrasion, etc. The bulk of the strength of the FRP is provided by the fibers. While the strength of the carbon fibers is 4,000 MPa (600 ksi) and higher, typical tensile strength values for carbon FRP laminates are around 930 MPa (135 ksi). More detailed about this process is presented later in this paper.

FRP products are anisotropic, meaning their material properties are not the same in all directions. The properties of FRP materials are controlled by the type, amount and orientation of the fiber being used. This behavior can be advantageous in design of pipes by orienting the fibers in the direction where strength is needed. For example, by applying the FRP with the fibers placed in the hoop direction, the pressure rating of the pipe in the hoop direction is enhanced. To resist longitudinal forces, FRP fabrics must be installed with the fibers aligned with the axis of the pipe. Some of the common standards for the strength of FRP include:

- Tensile strength per ASTM D3039
- Overlap splice shear strength per ASTM D7616
- Flexural strength of the resin per ASTM D790
- Compressive strength of the resin per ASTM D695

3. CARBON FRP DESIGN

The objective of the FRP design is to ensure the FRP liner will remain functional when subjected to service loads over its design life and have the necessary strength, reliability, and durability. At present, the only standard on pipe rehabilitation with CFRP is AWWA C305, which is exclusively written for prestressed concrete cylinder pipe (PCCP) rehabilitation. However, during the past decade many other types of pipes have been successfully repaired with FRP materials. The liner can be designed to satisfy all limit states related to one or both of the following two design approaches: CFRP liner acting as a stand-alone buried flexible pipe (AWWA Class IV), or CFRP as semi-structural liner partially relying on the host pipe to withstand the internal and external loads (AWWA Class III). The following limit states should be satisfied:

- Rupture of CFRP laminate in the circumferential direction mainly due to internal pressure;
- Buckling of CFRP laminate in the circumferential direction due to external loads, external pressures, and internal negative pressure;
- Rupture of CFRP laminate in the longitudinal direction due to pressure-induced thrust, Poisson effect of internal pressure, and temperature change, and due to differential radial expansion of pipe with variable stiffness along the length;
- Buckling of CFRP liner in the longitudinal direction due to temperature change; and
- Interlaminar shear failure mainly due to inadequate development length/adhesion between the sheets of fiber.

While some design equations are provided in AWWA C305, FRP design, particularly for semi-structural rehabilitation can be complex and may require computational modeling with the finite element method as well as testing for particular loading conditions on different FRP configurations. Stress concentrations are possible at seams, joints, cracks, and other surface irregularities.

Carbon fabrics are typically supplied in 600-mm (24-inch) wide rolls that are several hundred feet long. The thickness of the dry fabrics are approximately 0.05-0.08 mm (0.02-0.03 inches) depending on the weave pattern and the aerial weight of the fabric. Among the advantages of FRP products is that they are anisotropic, meaning that the strength of FRP is different in x- and y- direction and it depends on the amount of the reinforcing fiber that is present in each direction. As an example, one of the carbon fabrics commonly used on our projects is unidirectional and has an aerial weight of 943 g/m^2 (27.8 oz/yd^2) (Fig. 2). When this fabric is saturated with resin in the field and allowed to cure, it becomes a laminate with a thickness of approximately 1.3 mm (0.05 inches). If this laminate is tested in tension, it will require a breaking force of 6800 pounds per inch (1185 N/mm) width of the fabric to cause tension failure of the sample.

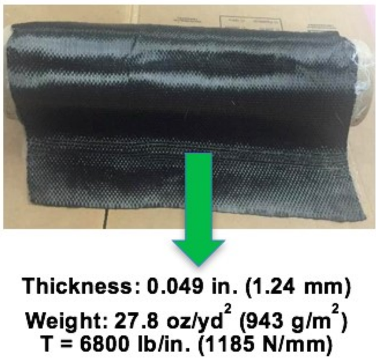

Fig. 2. Sample unidirectional carbon fabric.

To illustrate the design process, assume that a single layer of this fabric with a thickness of 0.05 inch is internally applied to the surface of the 120-inch diameter pipe. For hoop stresses, this band will be applied as a continuous ring inside the pipe with adequate overlap for continuity to develop the full capacity of the carbon fabric. The contribution of CFRP to resisting the hoop tension in the pipe can be calculated by considering a unit (1-inch-long) length of the pipe. The internal pressure will be (6800+6800)/120 = 113 psi (0.78 MPa). Adding an additional layer of CFRP will increase the pressure rating of this pipe to 1.56 MPa (226 psi). Note that by doing so, the radius of the pipe has been reduced by an insignificant amount of 1.3 mm (0.05 inch) per layer. In fact, in most FRP repair projects, the smooth surface and the reduced friction that will result from the repair will cause an increase (rather than a reduction) in the flow capacity of the pipe. In the foregoing simplified example, factors of safety and other reduction factors for environmental conditions, expected life of the repair, etc. have been ignored.

In locations where excessive longitudinal stresses require strengthening of the pipe, layers of the same unidirectional carbon fabric can be applied along the axis of the pipe. In repair of steel pipes with CFRP, care must be taken to avoid direct contact between the steel and carbon fibers which acting as dissimilar metals could result in galvanic corrosion. While the epoxy may provide adequate separation, a more conservative approach is to apply a layer of glass fabric as a dielectric barrier to the steel surface. This fabric will serve as a physical barrier to prevent direct contact between the carbon and steel.

The design drawings will include details of all the layers of FRP that will be applied, including the orientation of the fiber which is one of the most important factors in such designs. Any special surface preparation should also be noted. In application of FRP attention must be paid to apply the fabric under a slight tension to avoid any kinks. Otherwise, when subjected to tension, the fabric will want to rid itself of the kinks first before resisting any tension. Therefore, the application of FRP over sharp corners must be avoided as these will damage the fibers. Rounding of sharp corners or filling them with epoxy paste to achieve a radius of 25 mm (1 in.) is commonly specified. Details of how individual layers are applied and terminated in a recent steel penstock repair project are shown in Fig. 3.

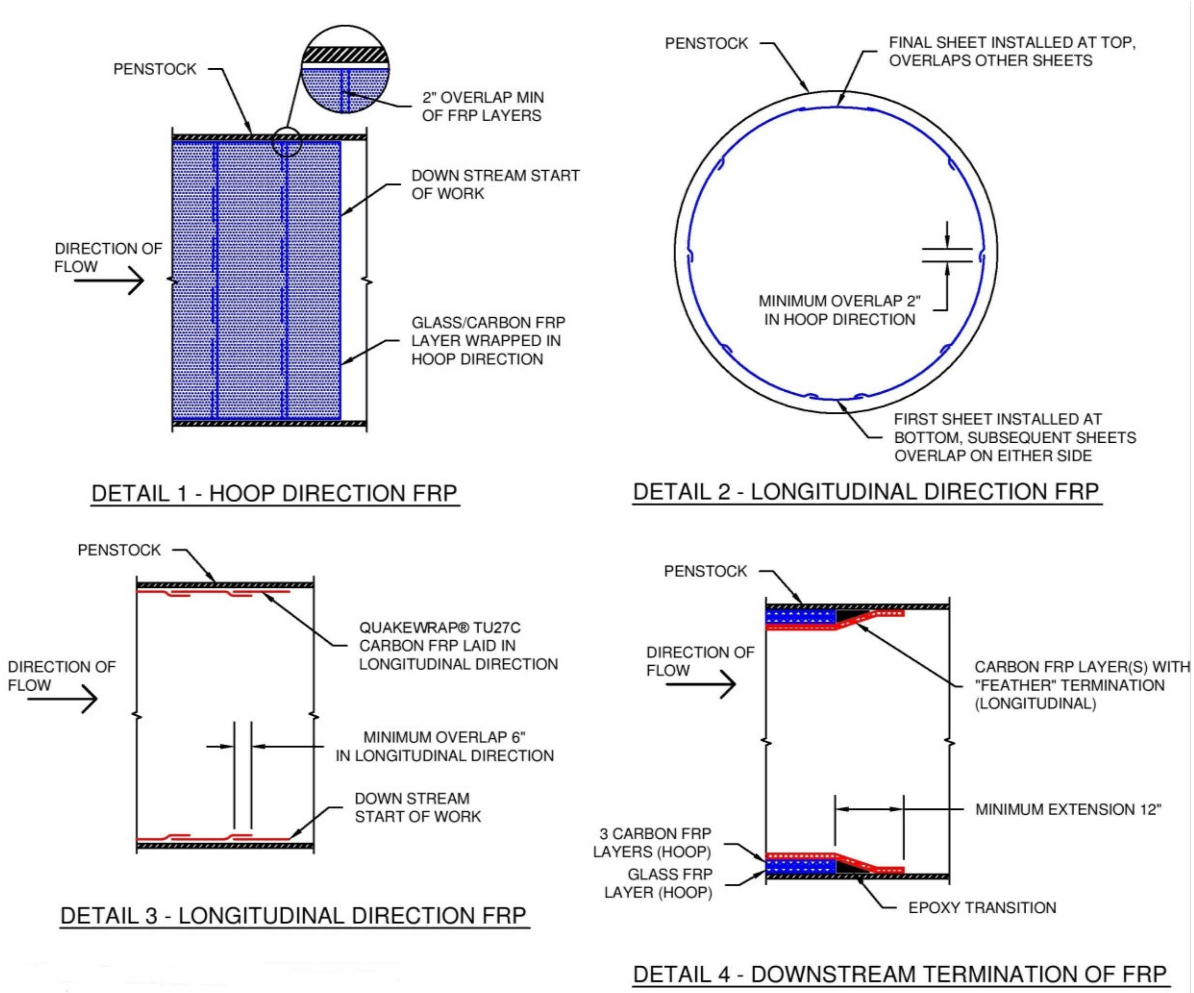

Fig. 3. Various details of the CFRP liner for a large diameter riveted steel penstock

Similarly, in riveted pipes, the areas around the rivets have to be filled with a mix of thickened epoxy. Such epoxy is very thixothropic and can be applied like a viscous paste. Figure 4 shows the detail for repair of riveted areas. The gentle slope produced by application of thickened epoxy ensures proper transfer of force.

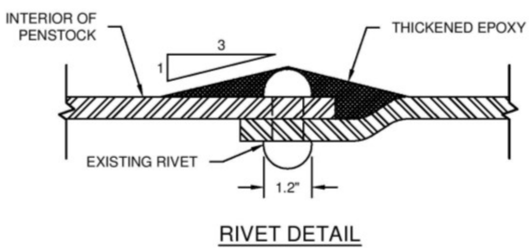

Fig. 4. Detail of preparation of the area around rivets prior to the application of CFRP.

Once the surface of the pipe has been cleaned, the glass fabric that serves as the dielectric barrier is applied first. The CFRP layers in the longitudinal direction are applied next. As shown in Detail 2 in Fig. 7, a small overlap of 50 mm (2 inches) is sufficient for these layers in the hoop direction since there are no fibers aligned in that direction. However, in the circumferential direction, the fabric bands must overlap 300 mm (12 in.) to ensure that the strength of the fibers in the hoop direction is fully developed. These overlap lengths are calculated similar to the development of steel reinforcement in reinforced concrete structures that is a familiar concept to structural engineers.

The top layer of FRP that is in contact with water, is usually installed with overlapping joints along the direction of the flow. This allows the water to flow from one band over the adjacent one (like shingles on a roof) and prevents the water to get between the FRP layers. The same concern exists at the upstream termination point of the liner. The high pressure water could potentially lift the edge of the FRP liner and cause a separation of the liner from the host pipe. There are two ways to address this issue. For concrete pipes, a keyway about 25mm (1 inch) deep by 75 mm (3 inch) long can be cut into the wall of the pipe; the top layer of the fabric is embedded in this keyway and the entire area is filled with thickened epoxy and made flush with the interior surface of the pipe. For steel or FRP pipes where such cuts are not practical, a metallic band such Weko seal or similar product can be place over the termination point. These bands are tensioned tight in place and provide a clamping force that will secure the liner tightly against the host pipe.

4. FIELD INSTALLATTION

The pipe segment targeted for repair must be completely drained of all standing water in the repair zone. Next, all required access points are opened, and applicable confined space work protocols implemented. For access points located in streets, proper traffic control measures must be implemented prior to the opening of the access.

The bond between FRP liners and the host pipe is critical to ensure proper structural performance of the lining. As such, proper surface preparation of the host pipe is necessary. The surface must be free of any loose material, oil, grease or any other surfactants that can impair the bond between the substrate and FRP. The surface is typically pressure washed to remove any loose material and debris. Additional cleaning measures (vacuuming, mopping, etc.) may be necessary prior to the next step, which is assuring the surface profile is within the specified range for a strong bond between the substrate and FRP. For concrete surfaces, the profile should be between concrete surface profile (CSP) 2 and 3 per the International Concrete Repair Institute (ICRI) guidelines; whereas, for steel surfaces the profile should be between 10 and 13 per the NACE International classification.

Abrasive methods are required to remove bond-inhibiting substances (such as scour, loose rust, etc.). The pull-off strength at the substrate-FRP interface is ascertained by field testing in accordance with *ASTM D4541and ASTM D7234* for steel and concrete surfaces, respectively. For concrete substrates, the surface shall be profiled using hydro surface profiling or other abrasive blasting to remove all contaminants (laitance, surface lubricants, broken mortar pieces, etc.) and to achieve a minimum profile of ICRI CSP 3 (refer to ICRI Guideline No. 03732). Heavily deteriorated substrate conditions may also require surface repairs, such as removing loose substrate material and corroded reinforcement, patching large voids, and injecting cracks. For steel substrates, the surface shall be prepared to near-white finish with all contaminants and salts removed from the surface.

Cured-in-place FRP liners are typically installed using hand wet layup method that allows the saturated fabric to be directly applied to the pipe surface and cured in place to generate an adhered laminate. Thus, when the liner is installed on the pipe interior surface, the size of the pipe on which it can be applied must be 900 mm (36 in.) or larger to accommodate the personnel, materials and safe access into the pipeline. However, a recently funded project by the Environmental Protection Agency is on developing an FRP system for repair of small diameter pipes, eliminating the need for man entry (USEPA 2019); this study will utilize both the field-saturated fabric and the pre-cured SuperLaminates described below.

There is no practical limitation on the maximum or minimum diameter of pipe that can be repaired when the FRP is installed on the exterior surface of the pipe. These liners can be applied over straight segments and complex geometry zones, such as bends, diameter transitions, or connection zones.

The technique commonly used to repair large diameter pipes is referred to as wet layup. The wet layup method requires saturation of the carbon or glass fabric prior to installation in the field. Mechanical saturators, such as the one shown in Fig. 5a are often used to guarantee fast, uniform saturation rates of carbon fabrics. The mechanical saturator is a device in which the unsaturated fabric roll is mounted, passed through a bath of saturating resin, and then passed in between two rollers that evenly spread the resin. The spacing between the rollers is calibrated to the fabric being used, and the spacing between the rollers is verified as part of the quality assurance/quality control (QA/QC) process. The saturated fabric is rolled up in a reel that can be taken off the machine and transported to the point of installation. In many cases, the saturating if fabric takes place outside the pipe although there are collapsible saturating machines that can be taken into the pipe from a 600 mm (24 in.) access port and reassembled inside the pipe.

Figure 5b illustrates carbon-fiber FRP sheets installed using the wet layup method where fabric applied to the walls has already been impregnated with epoxy using the mechanical saturator as shown in Fig. 5a. The fabric is hand pressed against the pipe wall to eliminate entrapped air pockets (blisters). The joints and terminations of repair must be detailed to prevent the water from penetrating behind the CFRP liner. The drawings provided by the design engineer must clearly show the orientation of the fibers, overlap joints and termination point details. In some applications, design may require installation of more than one layer of fabric. In those cases, the application of a thickened epoxy layer (called tack coat) between successive layers can assist with holding the saturated fabric in position so the wet fabric does not sag while the resin cures.

(a) (b)

Fig. 5. (a) Saturating machine, and (b) saturated carbon fabric being installed on a pipe surface using the wet layup technique.

5. RECENT ADVANCES IN FRP PIPES

The author has developed several new FRP solutions for repair or construction of pipelines in recent years. These unique products offer major advantages for certain applications and overcome the shortcomings of the wet layup system introduced above. In the following sections, two of these products, SuperLaminate and InfinitPipe® will be introduced. The third product called StifPipe® is a Class IV fully structural liner (Ehsani 2012b) and is presented in a separate paper in this conference (Ehsani 2019).

6. SUPERLAMINATE

The repair procedures described above uses the wet layup FRP technique. This technique requires properly trained technicians to prepare the resin in the field, saturate the fabric with resin and apply it to the structural member. Care must be taken to ensure the fibers of the fabric are aligned in the correct direction and to remove all air bubbles before the fabric is cured. As a result, the strength of the finished FRP product is greatly influenced by the experience of the installing team.

Over a decade ago, the author developed a new type of FRP product called, SuperLaminate (Ehsani 2010). These products are constructed with specially designed equipment. At the manufacturing facility, sheets of carbon or glass fabric up to 1.5 m (60 in.) wide are saturated with resin and passed through a press that applies uniform heat and pressure to produce the laminate shown in Fig. 6a. SuperLaminates offer several major advantages compared to fabrics described above:

a. By using a combination of unidirectional and/or biaxial fabrics, SuperLaminates provide strength in both longitudinal and transverse directions.
b. They offer higher tensile strength compared to wet layup fabrics; the tensile strength of the laminates ranges between 415 to 1070 MPa (60 to 155 ksi).
c. SuperLaminates are very thin with some products being only 0.25 mm (0.01 in.) thick; this affords significant flexibility to the laminate so that it can be coiled for repair of pipes having diameters as little as 50 mm (2 in.).
d. SuperLaminates are manufactured in plants under highest quality standards and the strength of the laminates can be tested *prior* to installation; in contrast, when the wet layup method is used, samples are made daily in the field for future testing and any defective material will not be revealed for several days until the samples are tested; this makes remedial measures difficult to implement.

Installation of the laminates requires a packer. Segments of pipe as long as 1200mm (4-ft) can be repaired with each application. The laminate is coated with an epoxy paste and it is wrapped around the packer. The assembly is pulled into the pipe and positioned at the repair location with the aid of a camera. At that time the packer is inflated, causing the SuperLaminate layers to slide outward until they meet the interior surface of the pipe. The assembly is left in that position until the epoxy paste cures. Next, the packer is deflated and pulled out, leaving the SuperLaminate behind. A video of this installation is available online (https://tinyurl.com/y632v5rf). If a length of pipe longer than 1.2 m (4 ft.) needs to be repaired, the above process can be repeated as many times as needed. The end of each newly installed laminate will overlap the previously installed laminate to give a shingling effect in the direction of flow.

This technology has been tested and approved for use in the gas industry, where old gas mains are being lined with a nonstructural liner (Carbone et al. 2012, Ehsani 2012a). Some of these lines include drip pots for collection of condensation that are no longer needed. When the liner spans across these openings, the pressure of the gas ruptures the liner. In other words, the liner must be supported by a host pipe throughout its length. In some cases, the drip pot may be as large as 600 mm (24 in.) wide. Once the pipe has been cleaned, a packer is used to deliver the 1200 mm (48-in.) wide SuperLaminate to the point of repair. The laminate bridges across the 600 mm opening, with a 300 mm (12-in.) length supported by the host pipe at each end. In essence, this allows building a new pipe remotely across a large opening. In this application, the use of flexible fabric would not be feasible since the packer and fabric assembly will bulge into the opening during the installation process. A video of this project is available at this link: https://tinyurl.com/y68hanyo

Recently, SuperLaminate is being used to repair casings in 500 m (1640 ft) deep wells in the mining industry. These wells are lined with 12 m (40-ft) long segments of 200 mm (8-in.) fiberglass pipe that are coupled together and lowered into the well. During testing of the pipe, it was recognized that some of the joints leaked. A special laminate was constructed with a biaxial carbon fabric. Figures 6b and 6c show the site and the SuperLaminate that is wrapped around the packer before it is lowered into the well. Once the laminate was installed and the epoxy paste hardened, the packer was deflated and pulled out of the well. The client conducted a pressure test to 4.1 MPa (600 psi) and proved the efficacy of the system. In that site, the mine will be spot repairing 30 such leaks with SuperLaminate in the coming weeks.

(a) (b) (c)

Fig. 6. Application of SuperLaminate to repair of pressure pipes: (a) Samples of SuperLaminate, (b) Site location for 500m (1600 ft) long pipe, and (c) SuperLaminate wrapped around a packer to be sent into the well.

7. INFINITPIPE®

FRP products lend themselves to construction of new pipelines too and there are many fiberglass pipe manufacturers worldwide. However, those companies manufacture the pipes in their plants and the pipe segments are shipped to the job site to be connected. This approach is not sustainable as the cost of transportation, especially for large diameter pipes, becomes prohibitively expensive as the distance between the job site and the manufacturing plant increases. Furthermore, the leaking at the joints is a major source of concern and maintenance that must be considered during the life of the pipeline; the leaking of the well linings in the mines that was described above is an example of such failures even in a newly-installed pipeline.

Recently, the author introduced the game-changing concept of an FRP pipe manufactured continuously on site, dubbed InfinitPipe® (Ehsani 2015). This technology has been supported by research grants from the US National Science Foundation and the US Department of Agriculture though their SBIR programs. The original concept for the Mobile Manufacturing Unit (MMU) is presented in Fig. 7. In this technique, rolls of resin-saturated fabrics of glass or carbon are helically wrapped around a mandrel. The mandrel is heated internally or externally and the special epoxy being used fully cures in a few minutes. Next, the finished pipe is slipped away from the mandrel, leaving a small length of the pipe at the tip of the mandrel. This process will continue endlessly, resulting in a pipe of any desired length. A special core can be sandwiched between the fabric layers to increase the rigidity of the pipe with little additional weight and cost. This new approach for construction of a pipe received the 2016 ASCE Innovation Award as the world's first green and sustainable pipe (Ehsani 2017). The finished pipe can be directly placed in an already cut trench as a new pipe or used for horizontal directional drilling (HDD) projects or as a liner to be pulled inside an existing pipe. A video of the original design of this equipment is available on YouTube https://tinyurl.com/y5cax8ca


(a)

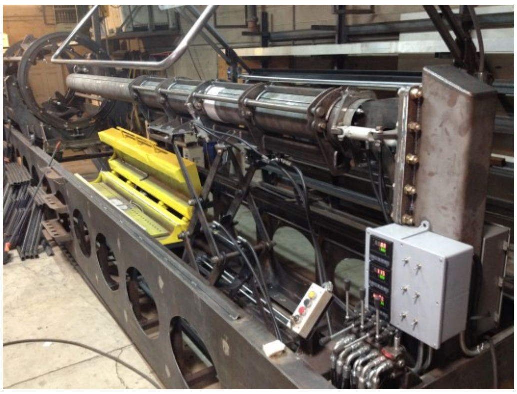
(b)

Fig.7. Views from the (a) left and (b) right ends of the first prototype of the Mobile Manufacturing Unit (MMU)

Some of the key features of InfinitPipe® are listed below:

1. It allows the construction of a pipe of any length and diameter on site.
2. The pipe can be designed for virtually any internal pressure.
3. The pipe has few joints so leaking will be minimized.
4. There will be minimal transportation cost compared to conventional pipes.
5. The FRP materials do not corrode, providing a long service life for the pipe.
6. No cathodic protection is required.
7. Eliminates the need for connecting pipe segments in the field, since the pipe can be directly placed in trench.
8. The pipe weighs only 10%-15% of conventional pipes.
9. Manufacturing of the pipe can begin within a short time after placement of the order, eliminating the waiting time to manufacture custom pipes.
10. InfinitPipe® is a green and sustainable technology.

With the latest research grant from the USDA that starts in September 2019, the design of the MMU shown in Fig. 7 will be modified and the size of the unit will be significantly reduced. The plan is to ship the MMU and one or two containers of resin-saturated fabric to the job site. Once the pipeline is constructed, the MMU will be shipped back for maintenance before it is shipped to another site in the world. This technology will truly revolutionize the pipeline industry, allowing development of many arid regions where the current high costs of water conveyance make such projects uneconomical.

The unique manufacturing process of InfinitPipe® lends itself to many applications where the use of conventional pipes can be challenging. Several of these applications are briefly described here. In recent years, global warming and rise in the temperature of oceans has caused bleaching of corals that cannot survive in these high temperatures. An innovative solution offered by the author was to build a series of large diameter InfinitPipe® on barges. As shown in Fig. 8 and in this video (https://tinyurl.com/yxac3zew) one end of the pipe is placed at the shallow warm region of the ocean and as the barge moves away into the deeper regions it continuously builds a pipe and places it at the ocean floor. Mechanical pumps activated with the wave action or powered by solar energy continuously pump cooler waters from the deep portion of the ocean to the shallow portions.

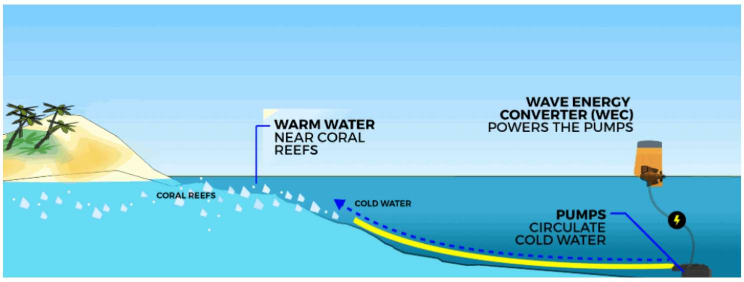

Fig. 8. Potential application of InfinitPipe® to solving the coral bleaching problem caused by global warming.

Another application is in insitu leaching. In this technique, thousands of wells are 500 m (1600 feet) or deeper are drilled on a grid close to each other. These wells are currently being lined with conventional pipes that are coupled together in the field. An acid solution is pushed through one pipe and it forces the metal out of the oars buried deep below the ground surface. The solution containing the metal is sucked up from adjacent wells. On the surface, these solutions are treated and the metal is extracted; the acid is recycled and sent back into the ground. Some of the joints at these pipes could leak, causing contamination of the ground water aquifer. Using the InfinitPipe® technology, a stationary version of MMU can be positioned directly above the well (Fig. 9). As the pipe is manufactured it is pushed into ground, creating a seamless pipe of any desired length. Such pipes can be manufactured at a rate of 0.3-0.5 m per minute. So, the operation can result in time savings as well.

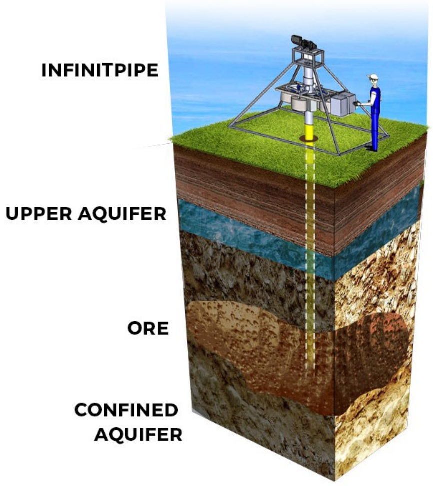

Fig. 9. Application of InfinitPipe® for insitu leaching in the mining industry.

8. QUALITY ASSURANCE

The different techniques described above for repair or construction of pipes vary extensively in the type of quality assurance that needs to be followed at different stages. SuperLaminate, for example, is fully manufactured in the plant, under well-controlled quality environment that reduces some of the concerns since the strength of the laminate can be verified in advance, before the repairs begin. InfinitPipe® that results in manufacturing of a new pipe in the field may require additional steps to ensure that the final product meets the project specifications. Several processes and steps must be followed to ensure quality control on these repair projects. Although the following are primarily aimed at repair of pipes using the wet layup technique, they do provide a framework for other applications introduced in this paper.

Quality control and assurance instructions are usually included in FRP project specifications and must be strictly followed by the installation contractor under the supervision of a certified inspector. The inspector must be present as soon as the pipeline is dewatered to inspect the existing substrate conditions and supervise surface preparation and repair procedures. The inspector must also record the ambient temperature and humidity inside the pipe before and during the installation of the FRP and during the FRP curing period. The inspector must also keep a record of the lot number of the resin and fabric roll used to fabricate each FRP strip and the location inside the pipe where each strip was installed. Similarly, the inspector must record lot numbers of containers and application locations of tack coats, top coats, and sealers. The overall objective of the inspector must be to ascertain that the FRP installation job is done in accordance with the project drawings and specifications.

The most common tests for FRP installations are witness panel and pull-off tests. Witness panels consist of 12 x 12 in. (300 x 300 mm) resin-saturated fabrics that are made periodically throughout the project. These panels are placed between two flat pieces of glass and allowed to cure in ambient condition. The panels are sent to a testing laboratory where they are cut into 1-in. (25 mm) strips and tested under tension loading. Pull-off or adhesion tests are performed by bonding a 1 or 2 inch (25 or 50 mm) diameter disc to the surface of the pipe or the FRP. The circumference around the disc is partially cored before the disc is pulled under direct tension with a special testing device. This test is used to determine the strength of the substrate, i.e. concrete pipe, and the bond between the FRP and the host pipe. An independent inspector usually observes witness panel preparation and adhesion pull-off tests performed by the contractor. Because pull-off tests are destructive, they may be performed on FRP liner mockups installed right next to the actual FRP liner. Tensile test reports usually include tensile strength and modulus of elasticity and ultimate strain at failure— values that are compared with the values given in the FRP manufacturer's product data sheet. Care must be taken to ensure that the laboratory performing tension tests on the FRP coupons has the right equipment and is familiar with the gripping requirements of such samples.

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