LATEST ADVANCES IN PIPELINE RENOVATION WITH FIBER REINFORCED POLYMER (FRP)

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Abstract

There has been a growing interest in the use of Fiber Reinforced Polymer (FRP) for repair and strengthening of structures, including pipelines in recent years. This paper focuses on the development of a new generation of FRP products called SuperLaminate. These sheets are produced in manufacturing plants per design specifications to meet the strength and stiffness requirements of the particular project. The products are stronger than conventional FRP and are installed in significantly less time. Among the applications are strengthening of pressurized pipes, repair of corrugated metal pipe culverts and joints in water and sewer pipes. A single roll can be used to repair any diameter pipe, making this a very versatile product.

Keywords
Fiber Reinforced Polymer (FRP), Pipes, Tanks, Culverts, Repair, Retrofit, Strengthening, Damage, Corrosion

1. INTRODUCTION

The water pipeline infrastructure worldwide is very old and in many cases has reached or passed the end of its design life. The American Society of Civil Engineers estimates that 6 billion gallons (23 billion liters) of potable and/or treated water is lost each day due to leaking and deteriorated pipes. The cost of bringing the U.S. water infrastructure to modern standards has been estimated to be in excess of 500 billion dollars. While in the last two decades various lining systems for repair and leak-proofing sewer pipes have been introduced, few options have been offered to repair pressurized water pipes.

For repair of smaller diameter water pipes where the resulting forces in the hoop direction are relatively small, polymer liners have been introduced that offer resistance to internal pressure. These are usually in the form of a soft tube made with a fabric or felt that is saturated with a polymer and is drawn or inverted into the pipe. Once in place, heat, steam, hot water or UV rays are used to cure the resin in place. Internal pressure may be used to force the tube radially outward into intimate contact with the wall of the host pipe. The liners are about 0.5 inches (13 mm) thick and can be used in pipes up to approximately 24 inches (600 mm) in diameter.

For larger diameter pipes, the conventional strengthening approaches are shotcreting or slip-lining the pipe with a smaller diameter steel pipe and filling the annular space between the host pipe and the steel liner with a grout. While effective, this technique has three shortcomings: a) it reduces cross sectional area of the pipe significantly, b) it requires an open cut to allow sections of the new pipe to be slipped into the host pipe, and c) it is difficult to apply in the bend regions of the pipe.

2. FIBER REINFORCED POLYMER

An alternative for repair of pressure pipes that overcomes the above shortcomings is to repair the pipe with Fiber Reinforced Polymer (FRP). FRP products are comprised of a reinforcing fabric, typically made of carbon or glass fibers that are saturated with epoxy resin in the field and applied to the interior surface of the pipe. The fabrics are supplied in width ranging from 24 to 50 inches (Fig. 1). The fibers that provide the structural strength of the fabric can be oriented solely along the length of the roll of fabric; this results in a fabric that is referred to as uniaxial. Alternatively, the fibers may be positioned along both the length and width of the fabric; this results in a fabric that is referred to as biaxial and these directions are marked as longitudinal (L) and transverse (T), respectively (Fig. 1).

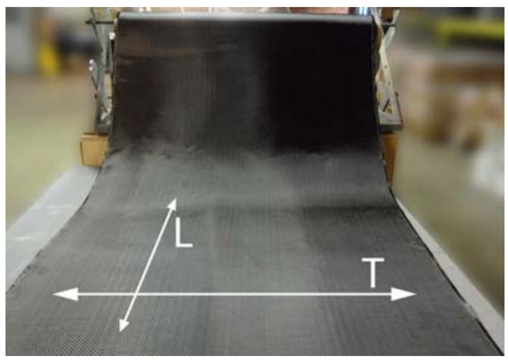


Fig. 1 – Biaxial carbon fabric with fibers oriented in both longitudinal (L) and transverse (T) directions.

The most common technique for application of FRP is referred to as the wet layup system, where the fabric is saturated with an epoxy resin in the field and it is bonded to the surface of the structural element. The curing of the resin is virtually completed within a day, resulting in a product that is much stronger than steel. Table 1 lists some of the typical material properties obtained by the wet layup procedure.

Table 1. Typical characteristics of Carbon FRP in wet layup systems

	Uniaxial	Biaxial
Ply thickness	0.04 in. (1 mm)	0.04 in. (1 mm)
Tensile Strength (Longitudinal Direction)	100 ksi (690 MPa)	70 ksi (480 MPa)
Tensile Modulus (Longitudinal Direction)	10,000 ksi (69 GPa)	6500 ksi (45 GPa)
Tensile Strength (Transverse Direction)	N/A	70 ksi (480 MPa)
Tensile Modulus (Transverse Direction)	N/A	6500 ksi (45 GPa)

The concept of strengthening of structures by external bonding Fiber Reinforced Polymer (FRP), i.e. the wet layup system, was first introduced two decades ago by the writer for strengthening concrete beams (Saadatmanesh and Ehsani, 1990). In the aftermath of the 1989 Loma Prieta earthquake, the writer extended that concept to retrofit deficient bridge piers by lateral confinement with FRP (ENR, 1990). What appeared to be unusual approaches at the time have since become mainstream techniques for repair and retrofit of structures worldwide.

In the ensuing years, the application of FRP was extended to repair and strengthen pipelines. The application of the original wet layup system and the newly developed pre-cured laminates in repair and strengthening of pipelines is the main focus of this paper.

3. REPAIR OF LARGE DIAMETER PIPES WITH WET-LAYUP 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, including pipelines. Since the late 1990s, a number of large diameter pipelines have been strengthened or repaired with FRPs (ICRI, 2008; Ehsani and Peña, 2009).

The technique used to strengthen pipelines with FRP to date is commonly referred to as wet layup. This technique requires properly trained technicians to measure and mix the resin in the field, saturate the fabric that is commonly supplied in 2-4 feet wide rolls and apply it to the inside surface of the pipe. Care must be taken to ensure the fibers in the fabric are aligned in proper directions and to remove all air bubbles before the resin is cured. Curing of the FRP takes about a day and the result is a structural liner that is typically two to three times stronger than steel. Figure 2 shows an 84-inch (2.1-m) diameter pipe repaired with glass fabric and epoxy resin using the wet layup technique.

(a) (b)

Fig. 2 – Repair of pipelines using the wet layup technique; (a) 4-ft wide band of fabric being installed, and (b) retrofitted pipe showing multiple bands of installed fabric.

Because FRP is an anisotropic material, its strength is derived from the amount and orientation of the fibers that are used to construct the fabrics. To ensure full development of forces, the overlapping joints must be properly detailed. For example, if the bands of fabric are applied in the hoop direction, the length of the band must exceed the circumference of the pipe by a length that will ensure continuity of fibers (or forces) in the hoop direction. Likewise, if the fabric contains fibers in two orthogonal directions, the adjacent bands of fabric must overlap a sufficient length along the axis of the pipe to develop the strength of the fabric in that direction. The result is a field-manufactured pipe with in a pipe.

4. PIPEMEDIC

On the twentieth anniversary of his first paper introducing the concept of repair and strengthening with FRP, the author introduced PipeMedic, a new form of FRP laminate product which offers major advantages in repair of many structural types including tanks and pipes (Ehsani, 2010).

PipeMedic™ is constructed with specially-designed equipment. Sheets of carbon or glass fabric up to 60 inches (1.5 m) wide are saturated with resin and passed through a press that applies uniform heat and pressure to produce the laminates (Figs. 3, 4). Typical properties for these laminates are shown in Table 2.

Table 2 - Typical properties of PipeMedic™

Property	Range of Values	
	U.S. Customary Units	S.I. Units
Thickness	0.007 – 0.03 in.	0.18-0.75 mm
Weight	0.1 – 0.3 pounds/ft^2	0.49-1.47 kg/m^2
Smallest Pipe Diameter that can be Repaired	3 in.	80 mm
Tensile Strength	50,000 - 155,000 psi	345 – 1,070 MPa
Tensile Modulus	3,500,000 – 13,500,000 psi	24,000 – 94,000 MPa

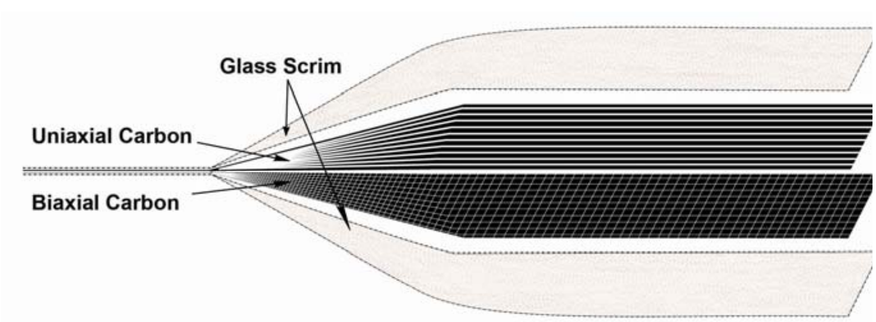


Fig. 3 – PipeMedic™ may be constructed with multiple layers of unidirectional or biaxial fabrics

Fig. 4 - From left to right: flexible carbon and glass PipeMedic™ laminates

PipeMedic™ offers several major advantages over the wet layup technique:

1) By combining unidirectional and/or biaxial fabrics, the laminates offer strength in both longitudinal and transverse directions (Fig. 3). This is a tremendous advantage that opens the door to many new applications, some of which are presented here.
2) With a thickness as low as 0.007 inches (0.18 mm), these laminates are flexible enough to be coiled for installation into pipes with diameters as small as 3 inches (80 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.
4) The manufacturing in an ISO-9000 certified plant ensures high quality products compared to the field-produced wet layup system.
5) Material properties can be tested before the laminates are installed on the pipe.
6) By moving most of the time-consuming activities from the construction site to the manufacturing plant, repair time can be reduced by as much as 80%.

Some of the applications of PipeMedic™ for rehabilitation of pipeline are described below.

4.1 Strengthening of Large-Diameter Pressure Pipes

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 in hoop stresses that 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 industrial plants. A common strengthening approach in the last decade has been to apply one or more layers of carbon fabric to the inside surface of the pipe. The author has been involved in such projects in a major U.S. nuclear power plant since 1998. While very effective, the time associated with the wet layup method has been a major drawback to this system.

PipeMedic™ significantly reduces the construction time. The flexibility of the laminates allows them to be packaged around cores that are 3 inches (80 mm) in diameter for ease of transport into pipes through access ports (Fig. 5). The ability of PipeMedic™ 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 other products such as cured in place (CIP) linings must be customized to fit a particular pipe diameter.

Fig. 5 – PipeMedic™ being taken into the pipe and installed; one size fits all pipe diameters

In larger pipes where man entry is possible, installation involves applying a thin layer of epoxy putty to the back of PipeMedic™ and pressing the laminate against the pipe surface. No effort is required to remove the air bubbles as the supper laminates are pre-cured and the manufacturing process eliminates all air bubbles. In fact, depending on the diameter of the pipe, the elastic memory of the coiled laminate may cause it to expand inside the pipe (like a loaded spring) and snap against the host pipe with little effort.

A typical application may include installation of bands that are 4-ft (1.2 m) wide. Continuity of PipeMedic™ in the hoop direction is achieved by adequate overlap length. That is, the length of each band will be longer than the circumference of the pipe by the required overlap length. Successive bands are placed adjacent to each other with the necessary overlap length to make sure that water will flow over one band of laminate onto the next one – like roof shingles.

The overlap length for successive bands along the length of the pipe will be calculated to ensure full development of forces in PipeMedic™. Thus if a 6-inch (150-mm) overlap is used, each 4-ft (1.2 m) wide band will effectively repair or strengthen 3.5 ft (1050 mm) of the pipe length. This allows strengthening of the pipe in both hoop and longitudinal directions with a single application of PipeMedic™.

Not only PipeMedic™ laminates are installed faster than the fabrics in a wet layup application, it is possible to include multiple layers of fabric into a single laminate, further reducing construction time. For example, when steel pipes require strengthening, a layer of glass fabric is typically applied to the surface of the pipe before any carbon fabric is applied (ACI 440, 2008); this is needed to avoid galvanic corrosion. This protective layer can be incorporated into the manufacturing of PipeMedic™, resulting in even further time savings. Thus instead of saturating and applying several layers of fabric to the pipe, the strengthening can be achieved by installing a single layer of PipeMedic™. This can reduce the construction time by as much as 80% in many projects. 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.

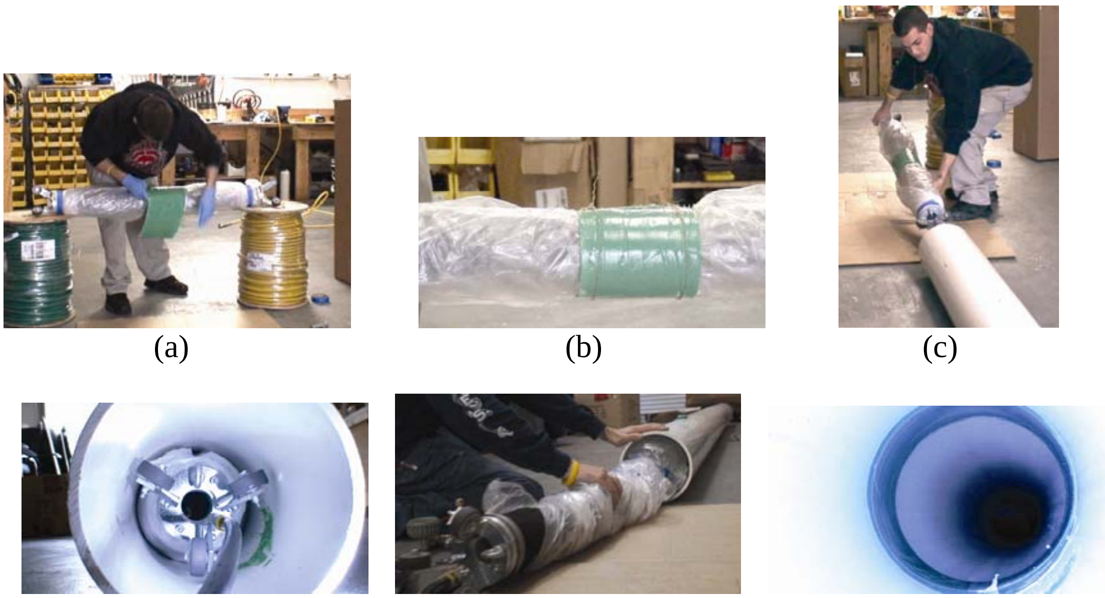
4.2 Repair of Small-Diameter Pipes

Few effective repair techniques exist for repair of small-diameter pipes that operate under pressure. One of the common techniques is to use a composite tube-shape lining that is made with felt or other types of fabric. The tubes are made in different diameters to fit a particular size pipe. Tube sections in lengths up to 1000 feet are saturated with resin and are either pulled through or inverted into the pipe. Once the liner is in the correct position inside the pipe, water, hot air or steam is commonly used to push the tube against the host pipe. The materials used for construction of these tubes are not that strong; typical tensile strength is an order of magnitude less than the FRP systems discussed above. This leads to fairly thick liners which will in turn reduce the cross section of the pipe and flow. A further disadvantage is that the tube-like liners ca be installed in very long sections. As such, they do not lend themselves to spot repair.

Thin super laminates can be easily wrapped around a packer to fit pipes with diameters as small as 3 inches (80 mm) (Fig. 6). A thin layer of epoxy is applied to the outer surface and the overlapping portion of the super laminate. The assembly is sent into the pipe and the packer is inflated to install the laminate against the pipe. A closed circuit TV camera can be used as a guide to ensure that the laminate is placed at the exact location where repair is needed.

Once the epoxy is cured, the packer is deflated and removed from the host pipe. In such a repair, the thin super laminate can increase the pressure capacity of the 3-inch (80 mm) pipe by over 350 psi (2.4 MPa). The impervious laminate also serves as a solution for repair of pressurized gas lines.

The above procedure is ideal for spot repair of pipes. Additional pieces can be similarly installed with a small overlapping length to repair or strengthen a larger length of the pipe. If the pipe is pressurized, the upstream edge of the installation must be sealed to prevent water flow between the host pipe and the laminate. This can be achieved by a mechanical seal installed over the end of the laminate.



(a) (b) (c)

(d) (e) (f)

Fig. 6 – Repair of a small-diameter pipe with PipeMedic™: (a) apply epoxy to outside of laminate and wrap it around packer; (b) hold laminate in position with strings; (c) insert assembly into pipe; (d) inflate packer and allow epoxy to cure; (e) deflate packer and remove it from pipe; (f) view of inside of pipe upon completion of repair.

4.3 Repair of Culverts

Concrete and Corrugated Metal Pipe (CMP) culverts are extensively used worldwide. Many of these structures are old and in poor state of repair. CMP culverts, for example, usually corrode at the invert (Fig. 7a) and in many cases the extent of corrosion is so severe that the pipe is no longer functional. If the pipe is large enough for man entry, the steps of repair can follow those shown in Fig 7.

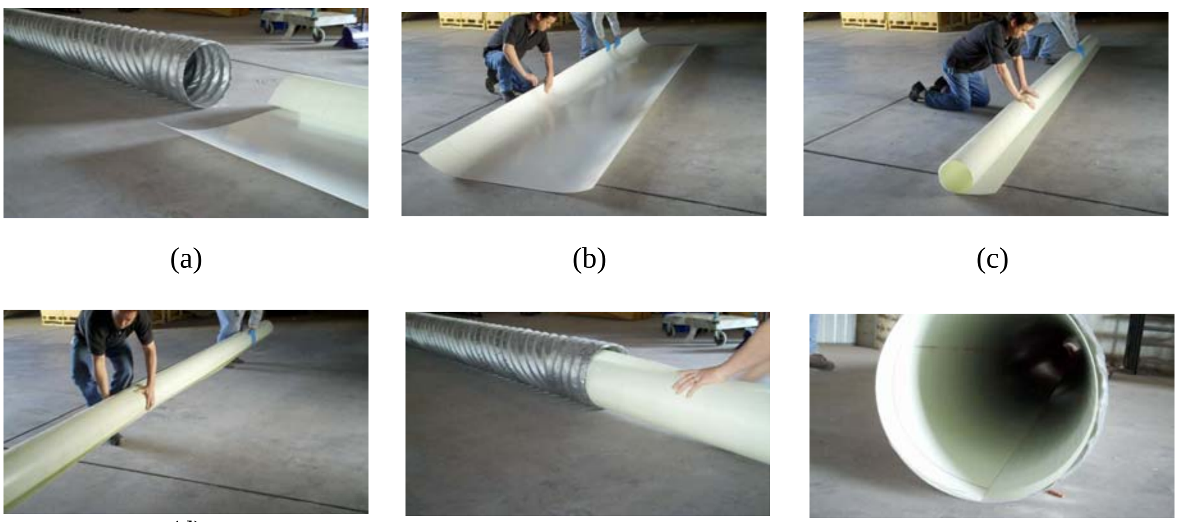
(a) (b) (c)

Fig. 7 – Repair of a culvert by installing overlapping 4-ft wide bands of PipeMedic™ laminate.

Four feet wide bands of super laminate can be cut to a length equal to the circumference of the pipe plus the required overlap length, typically 1-2 feet (300-600 mm) long. A layer of epoxy is applied to the back face of the super laminate before it is installed. It is sufficient for the laminate to be bonded only to the high points of the corrugation. The next layer of super laminate is then applied upstream, with a minimal 4 inch (100 mm) overlap (Fig. 6c). The edges at the two ends of the culvert can be sealed with a mortar to prevent water getting between the laminate and the host pipe.

The repair results in a pipe within a pipe which virtually has the same diameter as that of the host pipe. If the invert portion of the pipe is severely corroded, it can be filled with grout. However, in general, there will be no annular space between the super laminate and the host pipe that requires filling with a grout.

If the CMP culvert is too small for man entry, a possible method of repair is shown in Fig. 8. In this case, a 4-ft (1200 mm) wide piece of PipeMedic™ is cut to a length equal to the length of the culvert. The laminate is coiled into a tube form (Fig. 8b-c). A layer of epoxy is applied to the outer surface of the laminate and the overlapping portion. This is not shown in Fig. 8. Additionally, during the installation the laminate can be coiled into a smaller diameter to prevent the epoxy coated surface from coming in contact with the host pipe.



(a) (b) (c)

(d) (e) (f)

Fig. 8 – Steps involved in repair of a small-diameter culvert where man entry is not possible.

The coiled laminate is lifted (Fig. 8d) and is inserted into the pipe (Fig. 8e). The elastic memory of the laminate will force it to snap against the host culvert (Fig. 8f). If necessary, the ends of the pipe can be plugged and made air-tight. Then the entire pipe can be pressurized with air to ensure that the laminate is fully pushed outward against the host pipe while the epoxy cures.

4.4 Automated Installation

Repair of large-diameter pipelines with the wet layup system requires a crew of at least 4-5 workers per station. Because the FRP is being virtually manufactured in the field, the training and qualification of the crew plays a significant role in the overall success of the project.

In contrast, PipeMedic™ is manufactured in a plant. The strength of the laminate has been already "locked in" before the product is delivered to the job site. As a result, the process is nearly error proof and produces more consistent results. A small crew of 2-3 workers is sufficient for each station. The smaller trained crew size results in the contractor being able to set up multiple stations for the same pipeline without jeopardizing the quality of the finished repair. Additionally, the epoxy adhesive can be automatically measured, mixed and sprayed directly to the back of the super laminate sheets. This too will improve on quality and production rate.

We are currently developing a robot that would automate the entire installation process (Fig. 9). The wheels of the robot center it within the pipe and as the robot travels, PipeMedic™ laminate is installed in a continuous helical (spiral) manner. The angle or pitch of the spiral and the overlap length can be set by the technician. When completed, the robot will be capable of spraying the epoxy to the back of the laminate before installing it in the pipe.

Fig. 9 – Robot for installation of PipeMedic™ laminates in pipes.

5. 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 PipeMedic™ . This product is a major advancement that offers unique solutions to repair and retrofit of pipes that are not possible with conventional wet layup system.

PipeMedic™ is produced under high quality control conditions and meet ISO-9000 standards. It can be used in a variety of pipe repair applications for virtually all pipe sizes, with diameters as small as 3 inches (80 mm). The fact that the laminates are pre-manufactured can reduce pipeline repair times by as much as 80%. 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.

6. ACKNOWLEDGMENTS

The methods of construction and applications of PipeMedic™ laminates including the robot for installation of laminates discussed in this article are protected by several pending U.S. and international patents.

7. REFERENCES

ACI Committee 440 (2008). “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, (440.2R-08), American Concrete Institute, Detroit, MI.

Ehsani, M.R. (2010). "FRP Super Laminates: Transforming the future of repair and retrofit with FRP," *Concrete International*, American Concrete Institute, 32(3), 55-59.

Ehsani, M., and C. Peña, "Rehabilitate Pipelines with Minimal Downtime," *Opflow,* December 2009, 22-25.

ENR (1990). "Engineer says agency leaked idea," *Engineering News Record*, August 9, 1990, p.16.

ICRI (2008). "Restoration of Large Diameter Prestressed Concrete Cylinder Pipelines," *Concrete Repair Bulletin*, ICRI, Nov-Dec 2008, pp. 45-47.

Johnson, B., and Shenkiryk, M. (2006). "The Genesis of a Condition-Based Asset Management Program for Critical Water Pipelines," *Western Regional Trenchless Review,* 31-35.

Saadatmanesh, H. and Ehsani, M.R. (1990). "Fiber Composite Plates Can Strengthen Concrete Beams," *Concrete International*, American Concrete Institute, 12(3), 65-71.