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A NEW FRP SOLUTION FOR RECONSTRUCTION OF DETERIORATED PIPES AND CULVERTS

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ABSTRACT: Pipelines are a major component of the infrastructure that often get damaged by corrosion. In many cases, the repair may require restoring the strength of the pipe to its full original capacity, including the effect of external gravity loads. Access is always a challenge as these structures are buried deep and cutting trenches to replace the damaged pipe can add significant cost and time to the project.

This paper introduces a new type of Fiber Reinforced Polymer (FRP) pipe developed by the author that utilizes the sandwich construction technique to achieve high stiffness. The technique received the 2016 American Society of Civil Engineers (ASCE) Innovation Award as the world's first green and sustainable pipe. This technology allows two methods of repair. In one case a custom pipe can be built to any shape and size in segments of any length up to 10m long that can be used to slip-line the old pipe. In the other case, the host pipe is used as a mold to build a fully structural pipe below ground on site.

The paper focuses on three successfully completed projects in the US, Australia and Puerto Rico where both pressure pipes and gravity flow culverts have been repaired under some unique challenging conditions.

1. INTRODUCTION

Carbon Fiber Reinforced Polymer (FRP) was introduced in the late 1980s as a technique to repair and strengthen bridges and was later extended to repair pipes. A detailed description of the technology is available in a companion paper in this conference and for sake of brevity will not be repeated here (Ehsani 2019). In that paper, in addition to the conventional wet layup technique, two new products developed by the author, namely SuperLaminate and InfinitPipe® were introduced. This paper focuses on the development of a third product by the author named StifPipe®.

2. GENESIS OF THE INVENTION

In recent years, there has been a tendency towards designing liners where the liner not only resists the internal pressure of the pipe, but also the traffic and soil pressure. The latter assumes that at some point in the future the host pipe will fully disintegrate. While this may pose an extremely conservative view, it essentially requires building a new pipe inside the old pipe that could resist all internal and external loads independently of the latter.

The design of such pipes is controlled by buckling of the liner. The compressive strength of FRP products is lower than their tensile strength and the thin FRP sheets have little stiffness. That leads to installing layer after layer of carbon fabric inside a pressure pipe to create a thick enough liner with adequate stiffness. For such repairs, it is common to see designs calling for 12 or more layers of CFRP. In a typical project in the U.S., a single layer of carbon FRP including installation costs about $300 per square meter. A 12-layer system costs over $3500 per square meter of the pipe surface area. Both the high cost of repair and the long installation time required to accomplish the repair are major shortcomings of this system. Since many of these repairs must be performed under very tight schedules during a shutdown, shortening the repair time is of extreme value to the owners of these pipes such as power plants, water utilities, etc. Slip-lining of a deteriorated pipe with conventional pipes is another commonly used technique. However, this often results in a large annular space between the host pipe and the new pipe, leading to significant loss of flow capacity in the repaired system. The above shortcomings led to the development of the StifPipe® that is described here (Ehsani 2012).

3. StifPipe®

From an engineering point of view, the structure of a pipe must offer two primary attributes: a) sufficient strength and stiffness so it can be handled during installation and resist gravity loads safely, and b) adequate strength to resist the internal fluid pressure in both hoop and longitudinal directions. These can be separately addressed in the new pipe that uses carbon or glass FRP materials as the skin and a light-weight core material such polypropylene honeycomb panels or a 3D fabric. Carbon FRP has been successfully used for retrofitting of pressure pipes in the last 20 years. In StifPipe®, carbon FRP will be similarly used on the interior surface of the pipe to resist hoop stresses and thrust loads. One can take advantage of the anisotropy feature of FRP. That is, because the tensile strength of FRP depends on the direction of the fibers, the fibers can be oriented in the hoop direction to resist internal pressure; fibers that are positioned along the length of the pipe provide resistance against thrust. This unique feature of FRP can result in a more economical design.

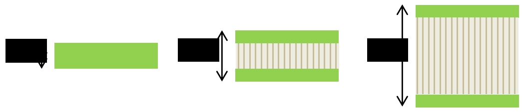
To increase the thickness and rigidity of the pipe at a low cost, a light-weight honeycomb core or 3D fabric is used as a spacer material, like the web of an I-beam. Additional layer(s) of carbon or glass FRP can be used as the outer skin of the pipe.

The properties of three types of fabrics are listed in Table 1. As an example, a typical layer of carbon FRP fabric is about 1.3 mm (0.05 in.) thick. Placing two layers on top of one another results in a total thickness T = 2.6 mm. However, as shown in Fig. 1, when these two layers are separated by a 7.5 mm (0.3-inch) thick honeycomb, making the total thickness 10 mm (0.4 in.), the stiffness of the panel is increased to 37 times while there is only a 9% increase in weight. This sandwich construction principle which is widely used in the aerospace industry (Baker et al. 2004), forms the basis of the design of the newly developed StifPipe®.

Table 1. Material properties tested according to ASTM D3039

Fabric Type	**VB26G**	**VU27G**	**TU27C**
Fiber type and architecture	Biaxial Glass	Unidirectional Glass	Unidirectional Carbon
Aerial Weight of Fabric g/m^2 (oz/yd^2)	884 (26)	918 (27)	945 (27.8)
Ply Thickness mm (in.)	1.0 (0.040)	1.3 (0.05)	1.2 (0.049)
Longitudinal (0°) Direction:			
Tensile Strength MPa (ksi)	372 (54)	586 (85)	930 (135)
Tensile Modulus GPa (ksi)	22.2 (3,217)	27.4 (3,980)	89.6 (13,000)
Ultimate Elongation	2.1%	2.3%	0.98%
Breaking Force N/mm (pound/inch)	380 (2,170)	611 (3,490)	1,190 (6,800)
Transverse (90°) Direction:			
Tensile Strength MPa (ksi)	269 (39)	---	---
Tensile Modulus GPa (ksi)	18.6 (2,700)	---	---
Ultimate Elongation	1.9%	---	---
Breaking Force N/mm (pound/inch)	273 (1,560)	---	---

The pipe can be designed for virtually any internal pressure by adding additional layers of carbon FRP on the inner surface of the pipe. The light-weight and inexpensive polypropylene honeycomb or 3D fabric provides the stiffness of the pipe, while the external FRP fabric layers increase the stiffness and provide durability for the pipe against environmental conditions. The non-corroding FRP materials eliminate the need for cathodic protection of the pipe.



RELATIVE STIFFNESS	1	7	37
WEIGHT (lb/ft^2)	0.910	0.978	0.994

Fig. 1. Comparison of stiffness of carbon FRP with carbon FRP applied as skin reinforcement to a lightweight polypropylene honeycomb core

StifPipe® weighs 10%-15% of a conventional fiberglass pipes, and is significantly lighter than steel or concrete pipes. A further advantage of this pipe is its ease of construction that allows manufacturing of a joint-free infinitely long pipe on the job site. All of the aforementioned factors contribute to the low cost of this pipe. In 2016, StifPipe® received the American Society of Civil Engineers (ASCE) *Innovation Award* as the world's first *green and sustainable pipe* (Walpole 2016).

Independent tests at the Louisiana Tech Trenchless Technology Center have characterized the behavior of this pipe under various loading conditions (Alam, et al. 2016). This paper focuses on three recently completed projects using StifPipe®. One case was a gravity flow culvert. Another included many pressure pipes in a power plant. The third was a deeply-buried large diameter tunnel with little access.

4. REPAIR OF CORRODED CULVERT

This project is located adjacent to the Wet Tropics of Queensland, a region of spectacular scenery and rugged topography with rivers, gorges, waterfalls, and mountains that has been recognized as a World Heritage Site by UNESCO. The area, which stretches along the north-east coast of Australia for some 450 km (300 miles), is made up largely of tropical rainforests (Ehsani et al. 2017a).

In late 2014, the Queensland Department of Transport and Main Roads (DTMR) identified a severely-corroded steel corrugated metal pipe (CMP) located on the Gillies Range Road in a deep gully in the rolling hills of the Atherton Tablelands in Far North Queensland. The site is about 1600 km (1000 miles) north of Brisbane and 60 km (40 miles) from Cairns. Rainfall in the area is very high (around 3 m), with very heavy tropical downpours during the "wet" season (December to May). The culvert serves a catchment of about 69 acres (28 hectares).

Constructed in 1963, the steel CMP pipe was 1.8 m (72 inches) in diameter and 26 m (85 feet) long, with a fill height above the top of the pipe of approximately 4 m (13 feet). A 600 mm (24-in.) diameter reinforced concrete pipe (RCP) located several meters away was enough to carry normal stream flows, with the CMP designed to carry flood flow. The Gillies Range Road is not a major transport route, but it is an important commuter route connecting the city of Cairns and the coast with farming communities on the Atherton Tablelands. Traffic consists primarily of commuters, tourists and small commercial vehicles, with average daily traffic of 2800, of which around 9.5% is commercial.

A detailed inspection in late October 2014 revealed that the pipe was suffering severe corrosion either side of an existing asphalt base, with complete separation of the lower (base) section from the upper section over significant lengths. In some locations where the base and walls had separated, there had been inward movement of the base relative to the walls of up to 50 mm (2 in.). Subsequent survey measurements throughout the pipe also indicated some "squashing" of the pipe. There was also significant settlement of the pipe beneath the embankment relative to the inlet and outlet. The diameter of the deformed culvert ranged between 1620 to 1800 mm (64 to 71 in.).

Repair alternatives. A number of parameters were considered in evaluating the various options for repair of this culvert. Some of the key factors considered were:

- Traffic disruption should be minimized. With no convenient alternative routes around the site, works would need to be carried out under traffic or by building a suitable side track.
- Works should be completed at the earliest opportunity - preferably prior to, or as soon as practicable after the "wet" season.
- Hydraulic capacity loss should be minimized to limit the impacts or reduce the cost of mitigating work.
- Equipment use should be minimized. Considering the remote location and access to the site, it would be preferred to minimize or eliminate the need for heavy lifting and jacking equipment.

Several conceptual treatment options were examined, including removal and replacement of the culvert with a new one, slip-lining with new concrete pipe segments, etc. The option selected was to reline the pipe with a self-supporting 1500 mm (59-in.) StifPipe®. The non-corroding FRP materials meet the expected service life of 50 years. The pipe met all the above criteria. The other secondary factors that contributed to the selection of this pipe included the opportunity to trial a new product for possible use in other locations, particularly in remote areas of Far North Queensland, and the opportunity to utilize the organization's direct labor workforce for installation of the product.

Design and construction of the pipe. The liner was required to conform to relevant structural design criteria in the following documents: a) The Australian Bridge Design Code (Australian Standard AS5100), and b) DTMR Document "Design Criteria for Rehabilitation of Circular Corrugated Metal Culverts". In addition, the following specific design requirements were specified:

- Design life - 50 years (minimum)
- Design live loads - SM1600 and HLP400 (per Australian Standard AS5100)
- Design fill heights under traffic lanes – 3.6 m (12 ft.) (min), 4 m (13 ft.) (max)

A field survey was conducted to measure the exact dimensions of the deformed culvert. The diameter ranged between 1620 to 1800 mm. Considering a pipe size that could be easily pushed through the culvert while leaving an adequate annular space for placement of grout, it was decided to build a StifPipe® with an outside diameter of 1500 mm. The ability to build the StifPipe® to virtually any desired shape and size is a major advantage that allows maximum use of the available space and reduces loss of flow capacity. In this case, the 25 mm (1 in.) thick wall of the pipe resulted in an inside diameter of 1450 mm (57 in.) which is significantly larger than any conventional pipe suitable for this project.

For ease of handling, it was decided to construct four pipe segments, each 6 m (20 ft.) long. Because StifPipe® is a recently developed concept in pipeline design, there are no industry guidelines that specifically address the design of such pipe. However, information on design of these structures is available for other industries, such as the aerospace industry where sandwich construction has been used extensively for decades. Other documents for design of FRP liners such as ASTM F-1216 and FRP pipes (ASTM D-2996) provide useful information that can also be utilized.

When a pipe is subjected to internal pressure, carbon FRP is typically used to resist that pressure. However, because on this project the pipe was subjected to gravity flow only, no carbon FRP was used. It is noted that glass FRP costs nearly 1/3 that of carbon FRP; so eliminating carbon fabric from the design also results in a lower cost pipe. The two types of glass fabric that were used on this project are listed in Table 1. VB26G is a biaxial glass fabric that contains glass fibers in both longitudinal and transverse direction. As this fabric is saturated with resin and wrapped around the mandrel, the fibers in the longitudinal direction provide the hoop strength and ring stiffness of the pipe; the fibers in the transverse direction align with the axis of the pipe and provide the axial rigidity of the pipe, like the strength of a beam under flexural loading. The other fabric, VU27G, is a unidirectional glass fabric with negligible fibers in the transverse direction. Therefore, this fabric primarily contributes to the ring stiffness and hoop strength of the pipe.

Two layers of a special glass fabric were used as the spacer elements to form the wall of the pipe. This fabric is comprised of two fascia layers of glass, connected with a series of short 8mm (0.31 in.) piles. Once the fabric is saturated, during the curing process the short piles soak up resin through capillary action and cause the fascia layers to separate from one another by 8 mm (0.31 in.). This results in a rigid and lightweight structure. The design of the StifPipe® for this project is shown in Fig. 2. The pipe construction includes the following layers of FRP products from the inside of the pipe moving towards the outside surface of the pipe:

- 1 Layer of VB26G
- 2 Layers of VU27G
- 2 Layers of 0.31-in. spacer fabric
- 2 Layers of VU27G
- 1 Layer of VB26G

This results in a pipe thickness of nearly 25 mm (1.0 in.).

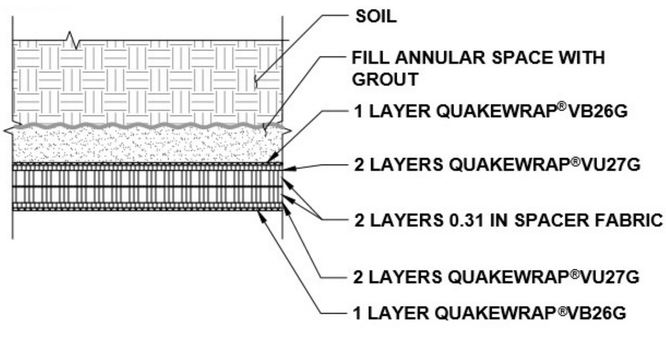


Fig. 2. Cross sectional view of StifPipe®

Construction of the StifPipe® begins by making a 6.7 m (22-ft) long steel mandrel. The mandrel includes telescopic arms that can be adjusted inward or outward to create a tube of virtually any shape and size (Fig. 3). A thin sheet metal is wrapped around the ends of the telescopic arms to complete the mandrel. The various layers of fabrics described earlier are wrapped around the mandrel in the proper order. The resin cures in ambient temperature in about 12 hours. If necessary, the mandrel can be heated from inside or outside to accelerate the curing process. The mandrel is partially collapsed, allowing the finished StifPipe® to be removed. The mandrel surface is then cleaned before the next pipe segment is manufactured. The process can be synchronized to follow a 24-hour schedule for construction of each pipe segment. The finished 4 segments of StifPipe® prior to shipment to the job site are also shown in Fig. 3.

Fig. 3. Construction of StifPipe® at QuakeWrap facilities in Brisbane, Australia

Field Installation. In an ideal situation, the manufacturing of the pipe segments would be performed very close to the job site to minimize transportation costs. For example, a temporary shed or a rented warehouse can be used for this purpose. However, considering that this was the first application of this technology in Australia, it was decided to build the pipe segments at the QuakeWrap facility in Brisbane. The four pipe segments were shipped on a truck to the job site and lowered with a crane in front of the culvert.

The original plan for installation was to support the pipe segments on casters and push them into the culvert. However, the corrugated geometry of the culvert would not allow for easy movement of the casters. Consequently, the caster trolleys were positioned upside down along the length of the culvert (Fig. 4a). Each segment of StifPipe® weighs only about 450 kg (1000 lbs); these light segments were placed over the casters and pushed by hand into their final position. The light weight of the pipe allowed this operation to be completed with only two men pushing the pipe in place (Fig. 4a). Short pieces of PVC pipe were wedged along the sides and top of the culvert to maintain the annular space between the culvert and StifPipe®.

(a) (b) (c)

Fig. 4. (a) Caster trolleys inside the culvert allowed pushing lightweight StifPipe® segments by hand into the culvert; (b) joining of segments with wet layup; (c) finished project.

Once the proper alignment of all 4 StifPipe® segments was achieved the ends of these pipes were connected using a wet layup system. As shown in Fig. 4b, a 300 mm (12-in.) wide band of VB26G glass fabric was saturated with resin and applied along the joint in the hoop direction. Grouting operations were affected by coring through the roadway. Cores were drilled in the roadway surface, penetrating through the CMP culvert and a cementitious grout was introduced to fill the annular space between the culvert and the liner. The headwalls at both ends of the culvert were formed and built with concrete (Fig. 4c). A video of this project is available online at the following link: (https://tinyurl.com/y6ag4lhf).

Schedule and Cost. One of the advantages of the technique presented here is the relative speed of construction. The custom-made pipes took about two weeks to build. Field installation of the segments and grouting operation was completed in 5 days. The only disruption of service to traffic was a few hours while the pipe segments were being offloaded from the truck and during the drilling operation. Total cost for this project was approximately US$ 250,000 with nearly 50% of the cost spent on the manufacturing and delivery of the four StifPipe® segments to the site.

5. REPAIR OF PRESSURE PIPE

The client for this project was the Puerto Rico Electric Power Authority (PREPA) (Ehsani and Cortes 2017b). The utility company is responsible for generating electricity to serve the 3.67 million residents and nearly 4.2 million annual visitors to the U.S. territory. Aguirre power plant is Puerto Rico's largest electricity generating plant that serves the entire main island of Puerto Rico and its two adjacent islands Vieques and Culebra. The power plant was constructed in 1975 and is located in the city of Salinas, in the southern coast of the island. The overall facility is comprised of two main power plants: a thermoelectric plant which is diesel oil based and has a capacity of 900 MW, and a combined cycle plant which is fuel oil based and has a capacity of 592 MW.

There is a large network of pipelines ranging from 600 to 1500 mm (24 to 60 in.) in diameter under the entire plant, delivering cooling water to various parts of the plant or carrying the return water to be discharged in the Caribbean Sea. These pipes operate at a pressure of about 1-1.4 MPa (150-200 psi). There are many riser pipes with bolted steel lids throughout the plant that provide access to the pipe network.

In 2015, severe corrosion in one of these riser pipes resulted in the steel cover dislodging under pressure. The riser pipe lid was thrown nearly 30 m (100 ft.) away and luckily did not injure anyone. This led to an inspection of all riser pipes by the plant management. During this inspection, it was determined that several of these risers exhibited various degrees of corrosion near the ground level. As a result, it was decided to repair the upper 1.2 m (4 ft) of 29 riser pipes.

Repair Alternatives. The riser pipes were 36-inch diameter steel pipes coated with a cementitious mortar lining. The primary concern of the plant was to repair the risers expeditiously. The pipes were subjected to both internal fluid pressure as well as external load from the weight of the soil and traffic adjacent to the risers. Consequently, the plant desired a fully structural repair (Class IV) to resist these loads without reliance on the host pipe.

One of the alternatives for this repair would be to replace the upper 1.2 m (4 ft.) of the riser pipes with a new steel pipe. This would require excavating around the riser and providing temporary shoring for the surrounding soil, cutting, and removing the existing pipe. Then a new steel pipe would be installed and welded to the old pipe, and coated with mortar. Finally, the temporary shoring would be removed and the area around the riser pipe filled with backfill. This conventional repair would require significant time and disruption of service.

A second alternative considered was to repair the pipe with carbon Fiber Reinforced Polymer (FRP) using the wet layup technique. The technique has been successfully used for repair of similar steel pipes (Larson et al 2012; Ehsani et al. 2016). If the repair is to consider only the internal pressure of the pipe, one or two layers of carbon FRP is sufficient and the work can be performed quickly and at a reasonable cost. However, when external loads are to be considered, the design is controlled by the stiffness or rigidity of the liner. In this case, 6 to 7 layers of carbon FRP had to be applied on top of each other to build a thick FRP liner. This option is time-consuming and costly. Furthermore, the entire repair must be performed in the field, leading to a potentially lower quality installation and requiring knowledgeable installation crew that was not readily available on the island.

A third option considered was the use of StifPipe® that could be manufactured before the shutdown and installed quickly. Considering the pros and cons of the above alternatives, the plant management decided to use this option for the repair of the 29 riser pipes.

Design and construction of the StifPipe®. The project required designing a freestanding liner that would resist the external loads from traffic and the weight of the soil. In addition, the pipe had to be designed for an internal pressure of 2.75 MPa (400 psi), which is considerably higher than the operating pressure of 1.03 MPa (150 psi). The existing riser pipes had a diameter of 914 mm (36 in.) and were coated with a cementitious mortar. Based on field measurements it was determined that a StifPipe® with an outside diameter of 890 mm (35 in.) is the optimum size that would fit in the host pipe, allowing room for a small annular space to be filled with grout. This is one of the advantages of this technology that allows manufacturing of a pipe to virtually any shape and size.

For this project, the pipe consisted of the following layers from inside to the outside of the wall:

- 1 Layer of chopped strand mat
- 2 Layers of TU27C
- 1 0.31-inch spacer sheet
- 2 Layers of VB26G

Each of these layers serves a special purpose. The chopped mat, when richly saturated with resin provides an impervious layer that covers any small pinholes that may be present in the pipe surface. The two layers of TU27C unidirectional carbon fabric (Table 1) provide the hoop strength and form the basis for resisting the 2.75 MPa (400 psi) internal pressure of the pipe with adequate factor of safety. The spacer sheet acts as the web in I beams to increase the moment of inertia of the cross section and rigidity of the pipe. The two layers of VB26G biaxial glass fabric have fibers in both longitudinal and transverse directions. The longitudinal fibers in the fabric increase the hoop strength and ring stiffness or rigidity of the pipe while the fibers in the transverse direction of the fabric contribute to the strength of the pipe along its length. These fabrics also enhance the overall rigidity of the pipe.

When a pipe is subjected to internal pressure, carbon FRP is typically used to resist that pressure. It is noted that glass FRP costs nearly 1/3 that of carbon FRP; so, when possible, it is more economical to use glass fabrics. Each layer of resin-saturated FRP fabric is about 1.3 mm (0.05 in.) thick. For this project, the various layers of fabric and the spacer sheet result in a total wall thickness of nearly 15 mm (0.6 in.) for the pipe.

Because this project required many pipes each 1180 mm (46.5-in.) long, it was easier to use a long mandrel and build a longer pipe that would be cut later into smaller lengths. A 3.7 m (12 ft.) long mandrel was used and various layers of resin-saturated fabric were wrapped around the mandrel in the order specified above. A saturating machine was used to ensure that the fabric was uniformly and thoroughly saturated with resin. The gap between the rollers in the saturating machine can be set to the desired value to ensure the proper ratio between the resin and fabric. The pipes were produced in a closed space that was heated to accelerate the curing time of the pipe segments. The pipes were fully cured in 24 hours and stripped from the mandrel. Each 3.7 m (12-ft.) long pipe segment was cut into 1180 mm (46.5-in.) long segments. An additional layer of epoxy was applied to the interior surface of the finished pipe for added protection and to obtain a very smooth surface.

Because this project was on a fast track, it was decided to build the pipes in the manufacturer's facilities in Tucson, Arizona. The finished pipe segments were inspected and shipped via truck to Miami, FL. From there they were shipped to Puerto Rico by sea freight. It is noted that each pipe segment weighs only 36 kg (80 pounds) so the weight of the shipment was relatively small.

Testing. As part of quality control and to verify the validity of design assumptions, two pieces of the pipes were randomly selected from the production line and were tested under parallel plate testing according to ASTM D2412. As shown in Fig. 5, the behavior of the pipes is linear to failure. Furthermore, the load-deformation characteristics of both samples were nearly identical in the elastic range, indicating high quality of the construction. The average ring stiffness for the pipes for various deflection levels are listed in Table 2. These values are comparable to pipes made with HDPE or PVC and can be used for the design of the pipe subjected to external compressive loads.

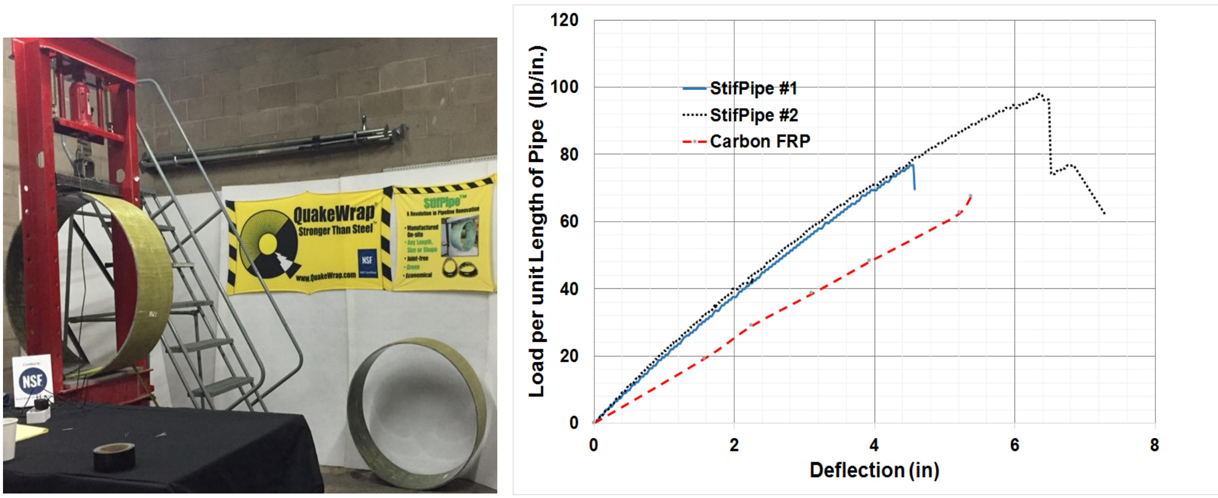


Fig. 5. Sample of StifPipe® being tested and the Load-Deflection results

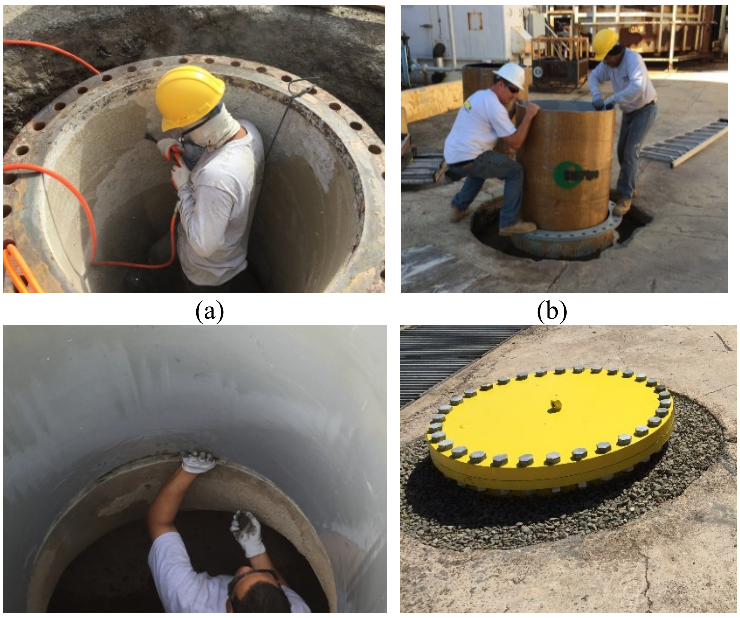
The dashed graph in Fig. 5 represents the results of an earlier test that was conducted for a different project (Ehsani 2102). In that case, a 914 mm (36-in.) diameter pipe with 6 layers of VU18C carbon FRP (without any spacer sheets) was tested. It is clear that the stiffness of StifPipe® carbon FRP pipe that takes advantage of the sandwich construction and a spacer sheet, is much higher than the plain carbon FRP pipe, even though the StifPipe® was built with only two layers of carbon FRP. This data proves the economic and strength advantages of the StifPipe® compared to the conventional wet layup solution that has been used to date.

Table 2. StifPipe® stiffness

Percentage of outside diameter		3%	5%	8%	10%
Deflection	mm (inches)	28.4 (1.12)	47.2 (1.86)	75.7 (2.98)	94.7 (3.73)
Pipe Stiffness for Sample # 1	kPa (psi)	136 (19.7)	133 (19.3)	127 (18.4)	121 (17.6)
Pipe Stiffness for Sample # 2	kPa (psi)	148 (21.5)	141 (20.5)	132 (19.2)	127 (18.5)
Average of two Samples	kPa (psi)	142 (20.6)	137 (19.9)	130 (18.8)	124 (18.0)

Field installation. The pipe segments were delivered to the jobsite and positioned next to the various riser pipes. A layer of the cementitious coating and laitance in the risers about 6 mm (0.25 in.) thick was mechanically removed (Fig. 6a) near the top of the riser; this created a horizontal ring/lip that would help support the StifPipe® in place. The lightweight pipes could be easily lifted by workers and lowered into the host pipe (Fig. 6b). An epoxy paste mixed with sand was used to seal the lower elevation of the annular space (Fig. 6c). An epoxy grout mix was placed in the annular space between the host pipe and StifPipe®.

As a part of this renovation project, the lids were also sandblasted to get rid of any corrosion. The lids were primed and coated with an epoxy and reinstalled using new bolts (Fig. 6d). A video detailing this project is available online at: https://tinyurl.com/yynmnpk7



(a) (b) (c) (d)

Fig. 6. Installation stages: (a) cleaning of riser, (b) inserting StifPipe®, (c) sealing the base and (d) placement of lid.

Schedule and cost. A primary advantage of the StifPipe® technology presented here is the timesaving in construction. In this case, the pipe segments were manufactured in Tucson and shipped to the jobsite. The construction of the pipes took about 7 days although a faster schedule could have been achieved if required. Field installation of the pipe requires few steps and is very fast. In this case, the field repair work took approximately 2 weeks but much of this time was spent on repair and painting of the riser lids. In many projects when the repairs can be scheduled in advance, the use of this technology results in major timesaving. The manufacturing of the StifPipe® segments, for example, can be performed outside of the repair window and while the pipe is in service. Once the pipe is taken out of service, the FRP pipe segments can be quickly installed. Unlike the wet layup technique, no waiting is required to allow the carbon FRP to cure inside the pipe.

The total cost for the manufacturing and shipment of the 29 segments of StifPipe® to the jobsite was approximately US$ 82,000. Installation was performed by a local contractor under supervision provided by the manufacturer's field staff. However, due to the variety of other tasks performed under the same contract, e.g. sandblasting and epoxy coating of the riser lids, etc. it is hard to determine the exact cost associated with the installation of StifPipe®.

It is noted that the StifPipe® technology presented here lends itself to continuous manufacturing of the pipe onsite (Ehsani 2015). A Mobile Manufacturing Unit (MMU) has been designed to fit in a standard freight container. The MMU can be shipped to any jobsite, where the pipe segments are produced, eliminating time delays due to transportation. For a project such as this one, the MMU would be able to produce the nearly 120-feet (37m) of pipe in less than half a day. The long pipe would be cut into shorter pieces onsite prior to installation.

6. WET LAYUP StifPipe®

The above two projects were such that segments of StifPipe® could be manufactured in advance and installed using the slip-lining technology. However, in some projects, access may be limited, and the finished pipes cannot be easily delivered to the point of repair. In these cases, the host pipe can be used as a mold and a rigid StifPipe® can be built directly on the host pipe, using the wet layup technique. One such major project that was recently completed is described below.

The project involved a 3.66 m (12 ft.) diameter concrete storm tunnel that is buried 33.5 m (110 ft.) below grade in Minneapolis, MN. Over a period of several years, a major leak was detected in the tunnel. The leak was created in a geological structure called the friable St. Peter which is a region of sandstone that the tunnel ran through. The presence of the tunnel in the sedimentary rock created a problem because the water was forced to run around it thus steadily eroding the sediment. Voids were created which caused underground streams to flow through the area, thus accentuating the problem. Two earlier attempts in 2016 and 2017 had failed to solve the problem. Minnesota Department of Transportation was concerned that the erosion of sandstone below could result in collapse of the roadways above. Excavating and replacing a tunnel at that depth would be a massive undertaking. Additionally, in the area of the leak, in some portions of the tunnel, the original wall thickness of 300 mm (12 in.) was reduced to a mere 50 mm (2 in.). This required a fully structural Class IV liner.

The engineers at the design firm Brierly Associates recommended the use of StifPipe® to the owner and the general contractor, PCi Roads. The project began in January 2019, in what turned out to be the coldest recorded in that area, -35° C (-32° F). The contractor decided on a new approach to stop the leaks: they would drill port holes near the tunnel invert to relieve pressure at the crown (Fig. 7a). The idea was to divert the water away from the voids above and into the ports below. This technique seemed to work and allowed the crew to pump 21 tons of grout into the void. After almost 3 years of trying, the leaks were finally plugged.

Access to this tunnel was only available through a 33.5 m (110 ft) shaft. Once inside the tunnel, skid loaders were used to drive the crew and the materials nearly 1 km (3200 ft.) to the point of repair. QuakeWrap engineers designed a StifPipe® consisting of two core layers and 8 layers of carbon FRP that considered internal pressure and and the effect of external loads on the tunnel. This resulted in a 32 mm (1.25 in.) thick pipe. A special moisture-insensitive resin was used for this project and the layers of StifPipe® were applied to the interior surface of the tunnel to create the new liner on site. Installation of the FRP was completed by FRP Construction, LLC (Tucson, AZ) (Fig. 7b). The total repair length was 6 m (20 ft.). The edges of the StifPipe® were feathered for a smooth transition to the host tunnel (Fig. 7c).

(a) (b) (c)

Fig. 7. (a) Leaks in the tunnel, (b) application of StifPipe® using wet layup, and (c) finished project.

There were, however, additional challenges. In order to install the StifPipe®, certain environmental conditions had to be met. Besides the absence of running water, the moisture at the tunnel surface had to be controlled. Wet layup is a "bond critical application" that required adherence to the host wall. That is not possible with high moisture present. Primer and adhesive coats were specially formulated by QuakeWrap for use underwater. The extreme low temperatures required special transportation considerations to ensure that the resins sent to the workplace did not freeze.

The area inside the pipe was sealed-off with plastic sheets to obtain a humidity and temperature controlled environment. Water that gathered upstream at a bulkhead was pumped through the scaffolding in the repair area using bypass pipes. Moisture and temperature readings along with pull-off tests were continuously recoded during the installation process and work overseen by inspectors from Brierley and MNDOT. After 3 weeks, the StifPipe® was finished in time for Spring rain and melting snow.

7. SUMMARY AND CONCLUSIONS

This paper summarizes the development of a new sandwich construction pipe called StifPipe® for use in repair of pipes. The examples included demonstrate applications where pre-manufactured segments of StifPipe® can be used to repair gravity flow culverts and pipes that operate under pressure. Another example shows how this technology can be applied using the wet layup technique. This is particularly beneficial in projects where access limitation does not allow the use of slip-lining technique. The light weight and ease of installation are among the key features of the pipe that has been presented. As a result of these successful applications, other similar projects have been identified for repair with StifPipe®. These factors have also contributed to the new design being recognized by the ASCE Innovation Award as the world's first green and sustainable pipe.

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