ASCE Innovation Award Winner: Sandwich Construction Carbon FRP Pipe

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ABSTRACT

This paper presents two field applications of a newly developed pipe that is constructed of Fiber Reinforced Polymer (FRP) products using the sandwich construction technology. The pipe, named StifPipe®, received the 2016 ASCE Innovation Award as the world's first green and sustainable solution for repair and construction of pipelines. Unlike conventional pipes that have a solid wall, the wall of this pipe consists of a lightweight honeycomb core that is covered on the outside and inside with one or more layers of FRP – a technology that has been used for decades in the aerospace industry for construction of fuselages. Segments of this pipe can be easily made by hand and used to repair pipelines following the slip-line technique. The technique allows the use of fewer layers of Carbon FRP and significantly reduces repair costs.

In one application, 29 corroded manholes in the Aguirre Power Plant, Puerto Rico were repaired. The steel manholes were 36 inch in diameter and the design pressure for the system was 400 psi. The 4-ft long sandwich pipe segments had an outside diameter of 35 inch and were lowered into position. The small annular space between the host pipe and the liner was filled with a grout. The rigidity of the pipe can support the lateral loads from the soil and nearby traffic. The premanufactured pipes reduced the repair time significantly. The project was completed in February 2016.

The other applications was for repair of a corroded corrugated metal pipe culvert in Australia. A 78-ft long, 59-inch diameter culvert in a remote site more than 1000 miles north of Brisbane had deteriorated and partially collapsed to a diameter of 55 inches. The four custom-made pipes manufactured in Australia were twenty feet long each, less than 1 inch thick and had an outside diameter of 51 inches. The lightweight pipes could be pushed by hand into the culvert, eliminating the need for jacking equipment on site. The repairs were successfully completed in 4 days in July 2015 with no traffic disruption.

INTRODUCTION

Carbon Fiber Reinforced Polymer (FRP) was introduced in the late 1980s as a technique to repair and strengthen bridges (Ehsani and Saadatmanesh 1990). FRP is comprised of fabrics of carbon or glass that are saturated with epoxy resins. In a process known as wet layup, the fabric is saturated with resin in the field and is bonded to the surface of beam, column or pipe; upon curing in several hours, it becomes 2-3 times stronger than steel. The high tensile strength, light weight, durability and ease of installation have made these products very popular in repair and retrofit projects

The use of wet layup FRP to strengthen pipes began in the late 1990s for Prestressed Concrete Cylinder Pipes (PCCP) and the technique has gradually extended to cover pipes made with steel and fiberglass. Wet layup is an efficient method to retrofit weak segments of pipes. In this trenchless repair technique, the crew can enter the pipe through access ports and apply carbon or glass fabric to the interior surface of the pipe. Once the fabric cures, it creates a pressure vessel that can relieve the host pipe from carrying all or part of the internal pressure. This technique is fairly well accepted and recognized by the industry and we have received major awards for such projects (ICRI 2008). The efficiency of this repair technique is further demonstrated in a recent project where 1750 m of a 2100-mm pipe in a remote mountainous site in Costa Rica was repaired in only 15 days (Ehsani and Pena 2009).

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. A single layer of carbon FRP installed costs about $25 per square foot. A 12-layer system costs roughly $300 per square foot 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.

The other option for repair of pressure pipes is to slip-line them with a new steel pipe. In this case, a section of the host pipe is removed to allow a segment of a new pipe to be inserted into the host pipe. Next, an additional segment of pipe is welded in the field to the first segment and the two are pushed or pulled into the pipe, using special rigs capable of handling the heavy pipe assemblies. The process continues as long as the pipe is running straight; bends in the pipe must be handled differently and may require cutting a new access pit. Once the new pipe is in place, the annular space between that and the host pipe is filled with grout. A major shortcoming of this technique is that the new pipe has a diameter that is often 12 inches smaller than the diameter of the host pipe, leading to significant loss of capacity compared to the original pipe. The need for jacking equipment also adds to the repair cost.

The above shortcomings led to the development of the new sandwich construction carbon FRP pipe (Ehsani 2012). The pipe is marketed as StifPipe®, but in this paper it will be referred to by its generic name Sandwich Construction or SC pipe.

SC PIPE

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 SC pipe that uses carbon or glass FRP materials as the skin and light-weight polypropylene honeycomb panels or a 3D fabric as the core. Carbon FRP has been successfully used for retrofit of pressure pipes in the last 15 years. In SC pipes, 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 0.05 in. thick. Placing two layers on top of one another results in a total thickness T = 0.1 in. However, as shown in Fig. 1, when these two layers are separated by a 0.3-inch thick honeycomb, making the total thickness 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 SC pipe. 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

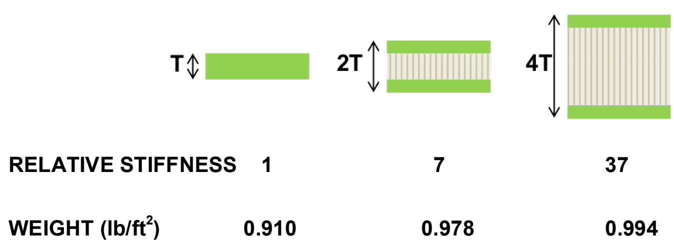

Fig. 1. Comparison of stiffness of carbon FRP with carbon FRP applied

conditions. The non-corroding FRP materials eliminate the need for cathodic protection of the pipe.

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 (oz/yd^2)	26	27	27.8
Ply Thickness (in.)	0.040	0.05	0.049
Longitudinal (0°) Direction:			
Tensile Strength (ksi)	54	85	135
Tensile Modulus (ksi)	3,217	3,980	13,000
Ultimate Elongation	2.1%	2.3%	0.98%
Breaking Force (pound/inch)	2,170	3,490	6,800
Transverse (90°) Direction:			
Tensile Strength (ksi)	39	---	---
Tensile Modulus (ksi)	2,700	---	---
Ultimate Elongation	1.9%	---	---
Breaking Force (pound/inch)	1,560	---	---

SC pipes weigh 10%-15% of a conventional fiberglass pipes, and are 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.

The above features offer unique advantages for the new pipe. In 2016, the American Society of Civil Engineers (ASCE) honored StifPipe® with its *Innovation Award* as the world's first *green and sustainable pipe* (Walpole 2016).

FIELD INSTALLATIONS

Two recently completed projects using SC pipe are reported here. One case was a gravity flow culvert. The other included many pressure pipes in a power plant.

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 Center by UNESCO. The area, which stretches along the north-east coast of Australia for some 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 1000 miles north of Brisbane and 40 miles from Cairns. Rainfall in the area is very high (around 10 feet), 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 72 inches in diameter and 85 feet long, with a fill height above the top of the pipe of approximately 13 feet. A 24-inch diameter reinforced concrete pipe (RCP) located several feet away was sufficient to carry normal stream flows, with the CMP designed to carry flood flow. The Gillies Range Road is not a major transport route, but 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 annual daily traffic (AADT) around 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 2 inches. Subsequent survey measurements throughout the pipe also indicated some "squashing" of the pipe and also that there was significant settlement of the pipe beneath the embankment relative to the inlet and outlet. The diameter of the deformed culvert ranged between 64 to 71 inches.

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.
- Waterway loss should be minimized to limit the impacts or reduce the cost of mitigating works.
- 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 59-in. SC FRP pipe liner. The non-corroding FRP materials meet the expected service life of 50 years. The pipe met all of 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 – 12 feet (min), 13 feet (max)

A field survey was conducted to measure the exact dimensions of the deformed culvert. The diameter ranged between 64 to 71 inches. 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 SC pipe with an outside diameter of 59 inches. The ability to build the SC pipe to virtually any desired shape and size is a major advantage of that allows maximum use of the available space and reduces loss of flow capacity. In this case, the 1 in. thick wall of the pipe resulted in an inside diameter of 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 20 feet long. Because SC pipe is a recently developed concept in pipeline design, there are no industry guidelines that specifically address the design of such pipes. 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. Experimental studies on the behavior of this pipe that were conducted at the Louisiana Tech Trenchless Technology Center (Alam, et al. 2016) also provided valuable insight into the design and behavior of this pipe.

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, similar to 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 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 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 1.0 in.

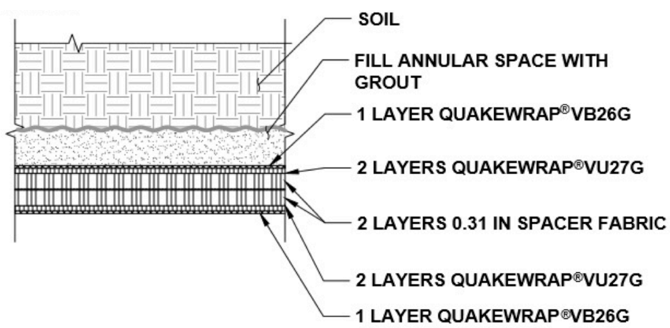

Fig. 2. Cross sectional view of SC pipe

Construction of the SC pipe begins by making a 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 SC pipe 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. Figure 4 shows the finished 4 segments of SC pipe prior to shipment to the job site.

Fig. 3. Construction of SC pipe 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. For example, a temporary shed or a rented warehouse can be used for this purpose. In cases where the pipe diameter is small, even the cargo trailer of a semi-truck can be used as a portable manufacturing facility that can be parked on the job site. 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 SC pipe weighs only about 1000 pounds; 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 SC pipe.

(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 SC pipe segments was achieved the ends of these pipes were connected together using a wet layup system. As shown in Fig. 4b, a 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. As shown in Fig. 4c, 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 detailing this project is available online (https://goo.gl/eCyjhH).

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. The 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 SC pipe segments to the site.

REPAIR OF PRESSURE PIPE

The client for this project was the Puerto Rico Electric Power Authority (PREPA) (Ehsani et al. 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. An aerial view of the power plant is also shown in Fig. 5.

There is a large network of pipelines ranging from 24-60 inches 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 150-200 psi. There are a large number of riser pipes with bolted steel lids throughout the plant that provide access to the pipe network (Fig. 5).

Fig. 5. Aerial view of Aguirre Power Plant (Salinas, PR) and typical pipe risers and lids

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 100 feet 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 4 feet 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) repair to resist these loads without reliance on the host pipe (AWWA M28).

One of the alternatives for this repair would be to replace the upper 4 feet 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 discussed above. The technique has been successfully used for repair of similar steel pipes (Larson et al 2012; Ehsani et al. 2016). When 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 very costly. Furthermore, the entire repair must be performed in the field, leading to a potentially lower quality installation and requiring knowledgeable installation crew that is not be readily available on the island.

A third option considered was the use of SC pipe 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 SC pipe. 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 400 psi, which is considerably higher than the operating pressure of 150 psi. The existing riser pipes had a diameter of 36 inches and were coated with a cementitious mortar. Based on field measurements it was determined that a SC carbon FRP pipe with an outside diameter of 35 inches 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 (Fig. 6):

- 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 400 psi (27.6 bar) 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 increase the hoop strength and ring stiffness or rigidity of the pipe while the fibers in the transverse direction contribute to the strength of the pipe along its length. These fabrics also enhance the overall rigidity of the pipe.

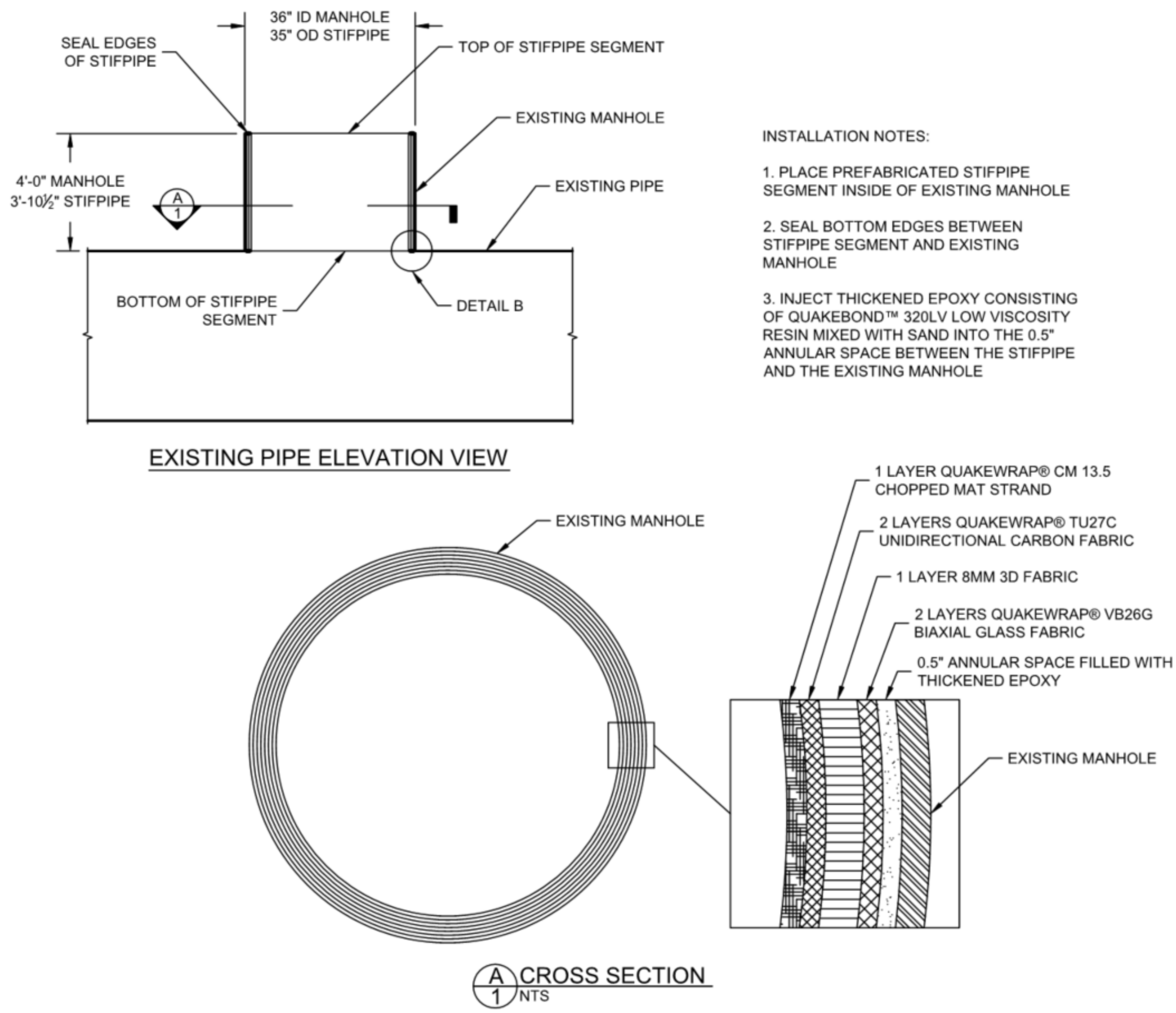

Fig. 6. Details of the SC carbon FRP pipe design for this project

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 0.05 in. (1.3 mm) thick. So, for this project, the various layers of fabric and the spacer sheet result in a total wall thickness of nearly 0.6 inches (15 mm) for the pipe.

Because this project required a large number of pipes each 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 12-ft long mandrel was used and various layers of resin-saturated fabric were wrapped around the mandrel in the order specified above (Fig. 7). 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 12-ft (3.66 m) long pipe segment was cut into 46.5-inch (1180 mm) 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.

Fig. 7. Manufacturing of PM carbon FRP pipe in Tucson and the finished pipe segments prior to shipment to Puerto Rico

Considering the relative ease of the manufacturing process, it is more economical to build these pipe segments close to the jobsite. A temporary facility such as a shed or a rented warehouse can be used for this purpose. However, in this instance because the 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 (Fig. 7). From there they were shipped to Puerto Rico by sea freight. It is noted that each pipe segment weighs only 80 pounds (36 kg) 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. 8, 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.

The dashed graph in Fig. 8 represents the results of an earlier test that was conducted for a different project (Ehsani 2102). In that case, a 36-inch diameter pipe with 6 layers of VU18C carbon FRP (without any spacer sheets) was tested. It is clear that the stiffness of SC 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 SC carbon FRP pipe was built with only two layers of carbon FRP. This data proves the economic and strength advantages of the SC pipe compared to the conventional wet layup solution that has been used to date.

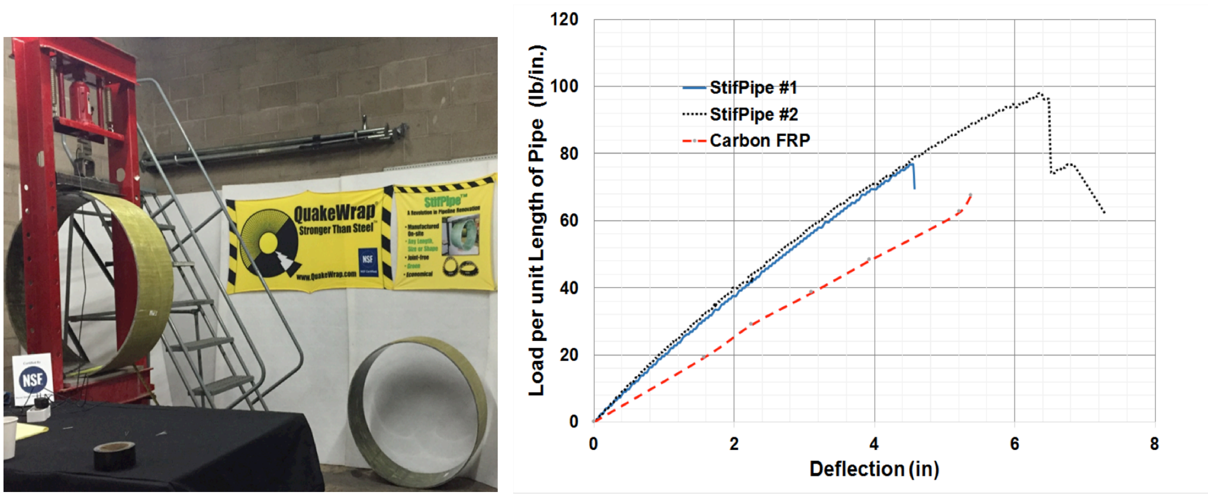

Fig. 8. Sample of SC carbon FRP pipe being tested and Load-Deflection results

Table 2. SC pipe stiffness (psi)

Percentage of outside diameter	3%	5%	8%	10%
Deflection (inches)	1.12	1.86	2.98	3.73
Pipe Stiffness for Sample # 1 (psi)	19.7	19.3	18.4	17.6
Pipe Stiffness for Sample # 2 (psi)	21.5	20.5	19.2	18.5
Average of two Samples (psi)	20.6	19.9	18.8	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 0.25 inch (6mm) was mechanically removed (Fig. 9) near the top 48 inch (1200 mm) of the riser; this created a horizontal ring/lip that would help support the PM carbon FRP pipe in place.

The lightweight pipes could be easily lifted by workers and lowered into the host pipe (See Fig. 10a). An epoxy paste mixed with sand was used to seal the lower elevation of the annular space (Fig. 10b). An epoxy grout mix was placed in the annular space between the host pipe and SC carbon FRP pipe (Fig. 10c).

The risers had also experienced corrosion from the outside over a height of about 9 inches (230 mm) below the grade. As a part of this project, the outside of the riser pipes were also repaired. The soil around the riser was removed to expose the pipe.

The exterior of the pipe was sandblasted to remove all rust and to achieve a near white metal surface. In repair of steel structures, care must be taken to prevent direct contact between carbon and steel. This contact of dissimilar metals can lead to galvanic corrosion. For this reason, a layer of glass veil saturated with resin was applied to the exterior surface of the pipe. This layer serves as a dielectric barrier to prevent contact between the steel and carbon FRP.

Fig .9. SC carbon FRP pipe segments placed by riser pipe and removing laitance from the interior surface of the pipe.

(a) (b) (c)

Fig 10. Installation process; (a) lowering of SC carbon FRP pipe into host pipe by hand, (b) sealing the bottom of the annular space, and (c) filling the annular space with grout.

A 9-inch (230 mm) wide band of TU27C carbon fabric was saturated with epoxy and wrapped twice around the exterior of the riser (See Fig. 11a). In addition to providing hoop strength and restoring the loss of capacity due to corrosion of steel, the FRP will serve as an impervious membrane that will keep oxygen and moisture away from the pipe. Because oxygen is the fuel for the corrosion process, eliminating oxygen will significantly reduce the corrosion rate.

The steel lids of the risers were also showing signs of pitting and corrosion. As a part of this renovation project, the lids were sandblasted to get rid of any corrosion. The lids were primed and coated with an epoxy (Fig. 11b) and reinstalled using new bolts (Fig. 11c). A video detailing this project is available online (http://goo.gl/OBIVre).

(a) (b) (c)

Fig. 11. Additional repairs included: (a) strengthening the outside of the pipe with carbon FRP, (b) epoxy coating the lids, and (c) installing the lids with new bolts.

Schedule and cost. A primary advantage of the SC carbon FRP pipe 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 SC carbon FRP pipe 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 PM carbon 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 SC carbon FRP pipe 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 SC carbon FRP pipe.

It is noted that the SC carbon FRP pipe 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.

SUMMARY AND CONCLUSIONS

This paper summarizes the development of a new sandwich construction (SC) FRP pipe for use in repair of pipes. The examples included demonstrate applications for repair of a gravity flow culvert and 29 pipes that operate under pressure. The light weight and ease of installation are among the key features of the pipe that have been presented. As a result of these successful applications, other similar projects have been identified for repair with SC pipes. These factors have 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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