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Puerto Rico Ushers in a "Green" Class IV Carbon FRP Liner

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1. Abstract

In recent years Carbon FRP liners have been used to repair pressure pipes. When the liner is to resist both external loads as well as internal pressure, the design leads to using many layers of Carbon FRP to build a thick rigid liner which is very expensive and time-consuming to install. This paper describes the first application of a newly developed FRP liner to repair a pressure pipe.

Twenty-Nine 36-inch diameter steel riser pipes (manholes) at the Aguirre Power Plant belonging to Puerto Rico Electric Power Authority (PREPA) were corroded and required repairing. Conventional repair with carbon FRP would be too costly and time-consuming. A custom-made FRP liner with an outside diameter of 35 inch was designed and constructed for the project. The liner consisted of two internal layers of carbon FRP for resisting the pressure, a lightweight core, and two external layers of glass FRP for added rigidity.

The 4-ft long pieces of pipe were manufactured away from the job site. Once access was granted, these liners were quickly inserted into the 29 host pipes and the small annular space between the host pipe and liner was filled with grout. The liners can resist both internal pressure of the system as well as external loads from soil and traffic.

The novel design and manufacturing process of this pipe has been recognized by the American Society of Civil Engineers as the 2016 recipient of Innovation Award for the world's first green and sustainable pipe.

2. Introduction

Puerto Rico Electric Power Authority (PREPA) is the primary utility company responsible for generating electricity to serve the 3.67 million residents and nearly 4.2 million annual visitors to the U.S. territory. Electric energy is produced by five main power plants: Costa Sur, Aguirre, San Juan, Palo Seco and Cambalache.

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 (Fig. 1). 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. 1.

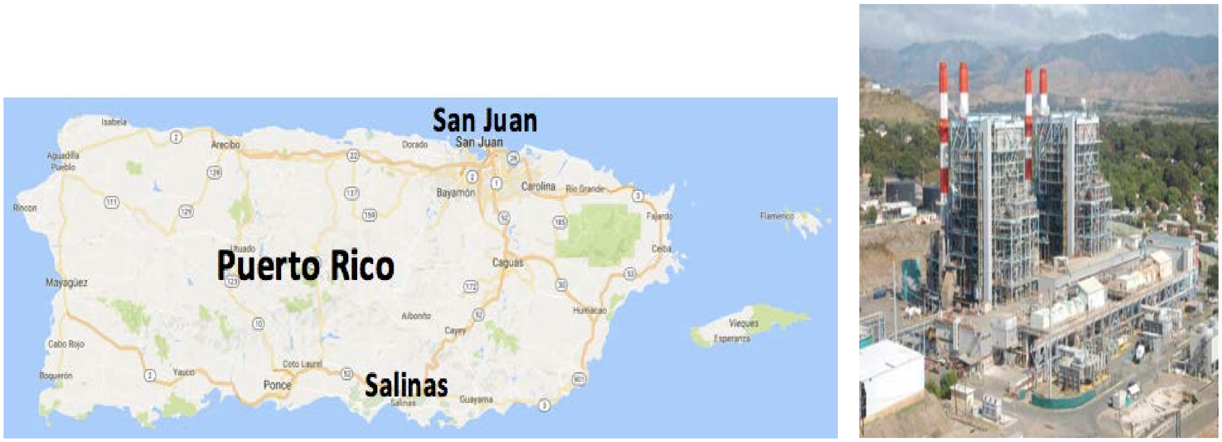


Fig. 1. View of Aguirre Power Plant located in Salinas, Puerto Rico

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 (See Fig. 2).

Fig. 2. Typical riser pipes with bolted lids throughout the power plant

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.

3. 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). In this system, referred to as wet layup, layers of carbon fabric will be saturated with epoxy resin in the field and applied to the surface of the pipe. 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. That means many layers of carbon FRP have to be applied on top of each other to build a thick FRP pipe. This option becomes 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 may not be readily available on the island.

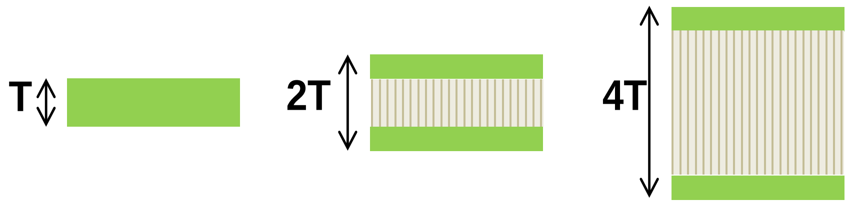
A third option considered was the use of the newly developed pre-manufactured carbon FRP (PM carbon FRP) pipe known as StifPipe® (Ehsani 2012). This pipe is made of Carbon FRP; however, the pipe is pre-manufactured in a more controllable plant setting using an experienced crew that leads to a higher quality product. The design of the pipe also reduces the number of layers of carbon FRP, which reduces the cost. Lastly, the installation of the pipe/liner in the field can be carried out much faster than the wet layup option described above.

Considering the pros and cons of the above alternatives, the plant management decided to use the third option for the repair of the 29 riser pipes.

4. Pre-Manufactured Carbon FRP 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 to resist gravity loads safely, and b) adequate strength to resist the internal fluid pressure in both hoop and longitudinal directions. These can be addressed separately in a pipe that uses carbon or glass FRP materials as the skin and lightweight polypropylene honeycomb panels or a 3D fabric as the core or spacer sheet. Carbon FRP has been successfully used for retrofit of pressure pipes for the last 15 years. In the proposed pipe, these same carbon FRP fabrics will be used on the interior surface of the pipe to resist hoop and thrust loads. In this portion of the design, the anisotropy feature of FRP is used. That is, because the tensile strength of the FRP depends on the direction of the fibers, one can orient the fibers 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 results in a more economical design. In this project, for example, only two layers of carbon fabric provide adequate strength to resist the internal pressure of the pipe in the hoop direction.

To increase the thickness and rigidity of the pipe at a low cost, a lightweight 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.



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

Fig. 3. Comparison of stiffness of carbon FRP with carbon FRP applied as skin reinforcement to a lightweight polypropylene honeycomb core

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. 3, when these same two layers are separated by a 0.3-inch thick spacer sheet, 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 principle is widely used in the aerospace industry (Baker et al. 2004) and forms the basis of the design of the newly developed 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 provide durability for the pipe against environmental conditions and corrosion. The non-corroding materials eliminate the need for cathodic protection of the pipe.

PM carbon FRP pipe weighs 10%-15% of a conventional fiberglass pipe, and significantly less when compared to steel or concrete pipes. These features offer unique advantages for PM carbon FRP pipe. In 2016, the American Society of Civil Engineers (ASCE) honored PM carbon FRP (StifPipe®) with its Innovation Award as the world's first green and sustainable pipe (Walpole 2016). In addition to the pressure pipe repair presented here, the pipe has been used to repair gravity flow culverts in the U.S. and Australia (Ehsani et al. 2017).

5. Design and Testing of the 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 was coated with a cementitious mortar. Based on field measurements it was determined that a PM 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 (See Fig. 4).

Because PM carbon FRP pipe is a recently developed concept in pipe design, there are no industry guidelines developed yet that specifically address the design of sandwich construction 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 for the design of PM carbon FRP pipe. Experimental studies on the behavior of this pipe that were conducted at the Louisiana Tech Trenchless Technology Center as part of the development of this product (Allouche and Alam 2014), and presented at the No-Dig Conference (Alam, et al. 2016) also provide valuable insight into the design and behavior of this pipe.

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 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.

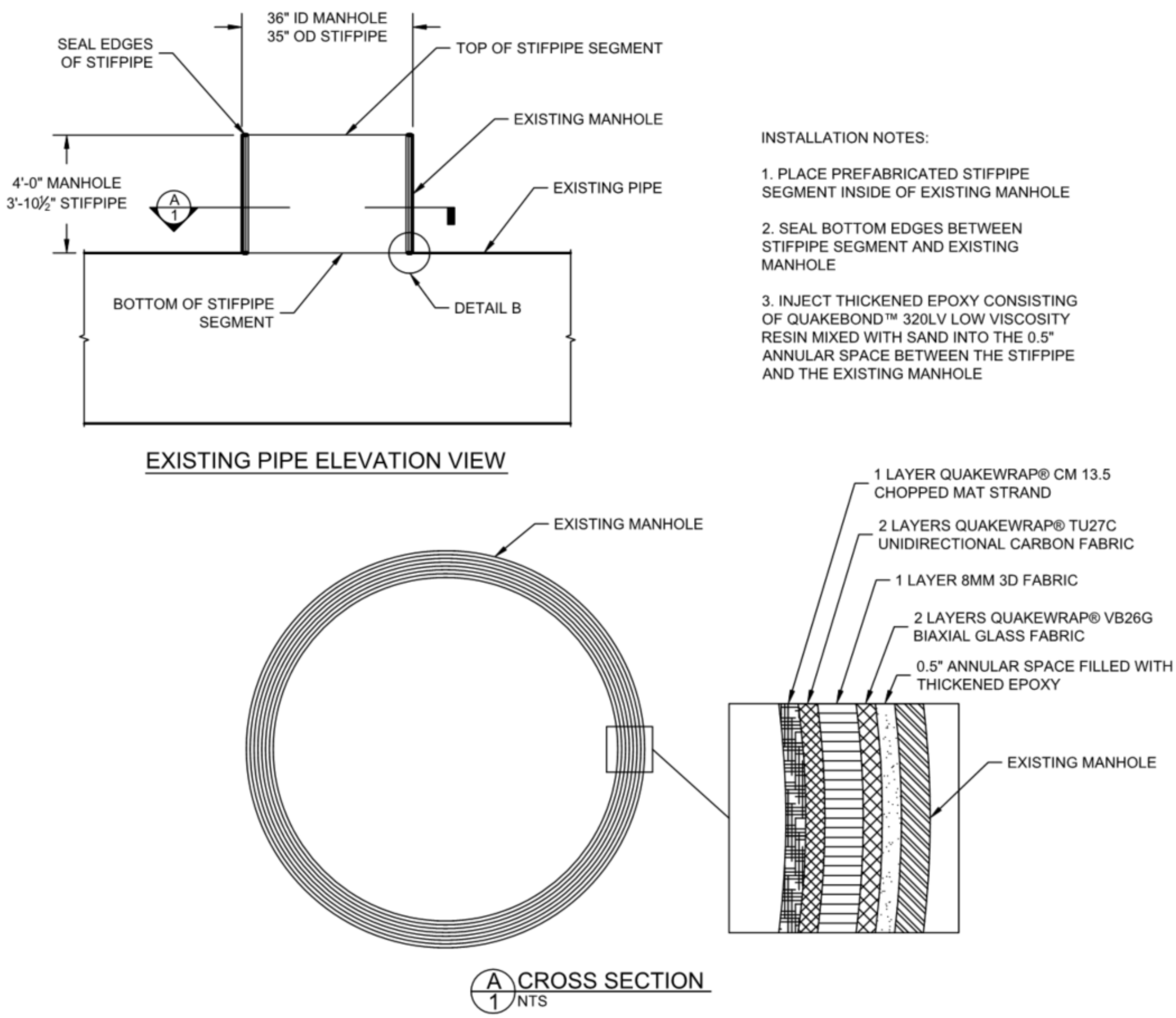


Fig. 4. Details of the PM carbon FRP pipe design for this project

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. The glass and carbon fabric that were used on this project are listed in Table 1. 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.

Table 1. Properties of fabrics saturated with epoxy resin

Fabric Type	**TU27C**		**VB26G**	
	US Units	SI Units	US Units	SI Units
Aerial Weight Fabric Only	27.8 oz/yd^2	943 g/m^2	26 oz/yd^2	880 g/m^2
Ply Thickness	0.049 in.	1.24 mm	0.040 in.	1.02 mm
Longitudinal (0°) Direction:				
Tensile Strength	135 ksi	930 MPa	54 ksi	373 MPa
Tensile Modulus	13,000 ksi	89.6 GPa	3,217 ksi	22.18 GPa
Ultimate Elongation	0.98%	0.98%	2.1%	2.1%
Breaking Force	6,800 lb/in.	1185 N/mm	2,170 lb/in.	380 N/mm
Transverse (90°) Direction:				
Tensile Strength	---	---	39 ksi	269 MPa
Tensile Modulus	---	---	2,700 ksi	18.6 G Pa
Ultimate Elongation	---	---	1.9%	1.9%
Breaking Force	---	---	1,560 lb/in.	273 N/mm

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.

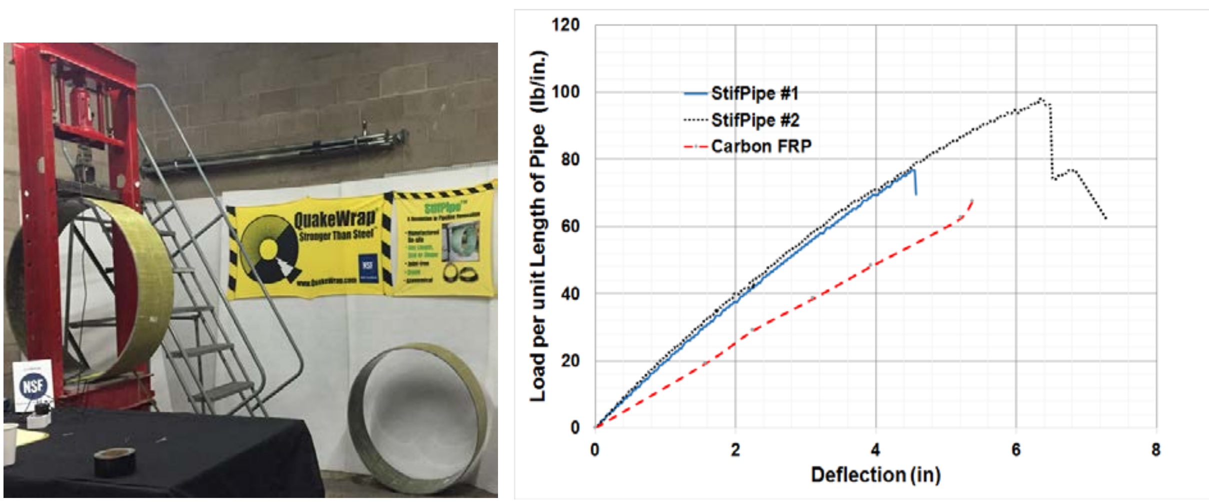


Fig. 5. Sample of PM carbon FRP pipe being tested and Load-Deflection results

Table 2. 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

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 36-inch diameter pipe with 6 layers of VU18C carbon FRP (without any spacer sheets) was tested. It is clear that the stiffness of PM 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 PM carbon FRP pipe was built with only two layers of carbon FRP. This data proves the economic and strength advantages of the newly-developed pipe compared to the conventional wet layup solution that has been used to date.

Because this project required a large number of pipes each 46.5-in. (1180 mm) 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. 6). 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 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.

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 facilities in Tucson, Arizona. The finished pipe segments were inspected and shipped via truck to Miami, FL (Fig. 6). 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.

Fig. 6. Manufacturing of PM carbon FRP pipe in Tucson and the finished pipe segments prior to shipment to Puerto Rico

6. 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 (See Fig. 7) 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. 8a). An epoxy paste mixed with sand was used to seal the lower elevation of the annular space (Fig. 8b). An epoxy grout mix was placed in the annular space between the host pipe and PM carbon FRP pipe (See Fig. 8c).

Fig .7. PM carbon FRP pipe segments placed by riser pipe and removing laitance from the interior surface of the pipe.

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.

(a) (b) (c)

Fig 8. Installation process; (a) lowering of PM 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. 9a). 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 (See Fig. 9b) and reinstalled using new bolts (See Fig. 9c). A short video detailing this project is available online (http://goo.gl/OBIVre).

(a) (b) (c)

Fig. 9. 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.

7. Schedule and Cost

A primary advantage of the PM carbon FRP pipe technology presented here is the time savings 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 time savings. The manufacturing of the PM 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 PM 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 PM carbon FRP pipe.

It is noted that the PM 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.

8. Summary and Conclusions

This project involved the repair of 29 riser pipes in a relatively remote site on the island of Puerto Rico. Test results proved how the use of the PM carbon FRP pipe technology could reduce the cost, speed up the construction schedule, and improve the quality of the finished installation. Furthermore, the technique nearly eliminated the need for local installers familiar with FRP applications. All of these parameters were of interest to the project owner. The project was completed on time and within budget.

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