International No-Dig 2014
32nd International Conference and Exhibition

Madrid
13-15 October 2014

Paper Ref # (also update in footer)
(the paper ref will be supplied to authors in an automated email)

InfinitPipe®: Developing a Revolutionary Onsite Manufactured Pipe

Mo Ehsani, PhD, PE[1]

[1]Professor Emeritus of Civil Engineering, University of Arizona and President of PipeMedic, LLC., Tucson, Arizona

ABSTRACT: This paper describes the development of a new type of pipe with a potentially significant impact on the pipeline industry. Unlike conventional pipes, the new pipe can be made on site having virtually any shape and size and to any length. This eliminates the need for frequent joints that are a major source of leakage and maintenance. The wall of the pipe uses a lightweight core that is reinforced on the inner and outer surface by carbon or glass fabrics saturated with epoxy. When completed, the Mobile Manufacturing Unit (MMU) will be able to produce around 500 m of pipe per day in a continuous process on site. With financial support from the U.S. National Science Foundation, preliminary tests on samples of this pipe that were manufactured by hand are reported here. The results indicate that the pipe can be a viable alternative to current pipes. Strength, stiffness, hardness and other aspects of the pipe were found to be comparable to other pipes that have been used to date. Case studies where short hand-made segments of this pipe have been successfully used in gravity flow and pressure applications are also presented. If the MMU is successfully developed, the light weight, ease of manufacturing, durability of the non-corroding constituent materials, elimination of much of transportation of finished pipe, etc. will make this the world's first "Green" and sustainable technology for pipeline manufacturing. The initial use of the pipe will be in moderate pressure projects for sewer and water pipes. However, adding more layers of carbon fabric can easily increase the pressure rating of this pipe. Thus, the pipe offers potential for use in oil and gas industries that operate at higher pressures.

1. INTRODUCTION

Progress in science and engineering is often evolutionary, with each new development advancing the field incrementally. Once in a great while, a revolutionary concept is presented where the rules of the game are re-written! This paper introduces one such case for the pipeline industry.

Construction of pipes requires fairly heavy equipment and complex manufacturing facilities. As a result, pipes are constructed in short segments and shipped to the job site, where they are joined together. The result is a pipeline with joints every 7-10m or so. These joints are potential sources of leaks, which can inflict significant loss of revenue as well as harm to the environment. For larger-diameter pipes, the transportation costs alone from the plant to the job site add significant expense to the project.

Fig. 1. Different layers comprising the wall of the proposed Honeycomb-FRP Composite Sandwich pipe

To overcome the above shortcomings, a new Fiber Reinforced Polymer (FRP) pipe is proposed (Ehsani 2011; Ehsani 2012) (Fig. 1). FRP products are comprised of fabrics constructed with carbon or glass fibers that are saturated with epoxy resin. When the resin cures, FRP reaches a tensile strength that is two to three times that of steel. The tensile strength of FRP is derived from the fiber content and fiber orientation. The resin serves as a binder that distributes the load among the fibers and protects the fibers from external damage.

FRP pipes made with glass fibers and resin such as those offered by Hobas® and Flowtite® have been in use for decades. However, the solid wall of these pipes makes them heavy and impractical for onsite construction. As explained in more detail below, the newly developed InfinitPipe® overcomes this shortcoming by using a lightweight honeycomb core for the construction of the wall of the pipe.

2. BACKGROUND AND GENESIS OF THE INVENTION

The use of carbon FRP for repair of large-diameter pressure pipes started in the late 1990s. One or more layers of a carbon fabric are saturated with epoxy resin and bonded to the interior surface of the pipe. Within several hours the resin cures in ambient temperature, creating a water-tight pressure vessel inside the host pipe that can resist significant internal pressure. Several such repairs including two large projects in power plants in the U.S. (ICRI 2008) and Costa Rica (Ehsani and Pena, 2009) that have been recognized by international awards provide more information on this technique.

In recent years, however, there has been a tendency by pipe owners towards requiring liners where the liner not only resists the internal pressure, but also the traffic and soil pressure; this 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 perform independently of the latter.

The design of such liners is controlled by buckling behavior of the liner. The compressive strength of FRP products is lower than their tensile strength. 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 not uncommon to see designs calling for 10 or more layers of carbon FRP, depending on the diameter of the pipe and the loading. In the United States, the cost of a single layer of carbon fabric installed in a pipe is around $250-$300 per square meter; so a 10-layer system can cost well over $2000 per square meter of pipe! Both the high cost of repair and the long time required to accomplish the repair led the writer to the development of this new pipe. As described later, once we recognized how easy it was to construct the short pipe segments for repair and slip-lining applications (called StifPipe®), we realized the real opportunity is to make longer pieces of this pipe onsite for use in new pipeline projects (called InfinitPipe®).

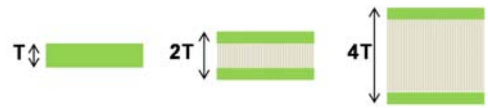
3. TECHNICAL APPROACH

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. These can be separately addressed in the new 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 the proposed pipe, these same carbon FRP fibers will be used on the interior surface of the pipe to resist hoop and thrust loads. In this portion of the design, we can take advantage of the anisotropy feature of FRP. 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 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 filler material, like the web of an I-beam. Additional layer(s) of carbon or glass FRP will be used as the outer skin of the pipe (Fig. 1).

As shown in Fig. 2, when a 2mm thick carbon FRP is sandwiched between a 6mm-thick honeycomb (making the total thickness 8mm), the stiffness of the panel is increased to 37 times while there is only a 9% increase in weight! This principle which is widely used in the aerospace industry (Baker et al. 2004), 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.

A typical HCS pipe weighs 10%-15% of a conventional fiberglass pipe, and significantly less when compared to a steel or concrete pipe. A further advantage of this pipe is its ease of construction that allows manufacturing of a joint-free pipe on the job site. All of the aforementioned factors contribute to the low cost of this pipe.



RELATIVE STIFFNESS	**1**	**7**	**37**
WEIGHT (kg/m²)	**4.436**	**4.767**	**4.845**

Fig. 2. Comparison of stiffness of carbon FRP with carbon FRP applied as skin reinforcement to a lightweight polypropylene honeycomb core

4. MANUFACTURING PROCESS

The primary materials for the construction of InfinitPipe® are: a) carbon or glass fabric supplied in rolls, b) epoxy resin supplied in drums, and c) honeycomb panels that are supplied as sheets or strips. All of these materials are light-weight, compact and they can be shipped in trucks to the job site. Thus, a container of raw materials can produce hundreds or thousands of meters of pipe, depending on the diameter of the pipe (Fig. 3). Prior to the construction of the pipe, a trench will be cut for placement of the pipe.

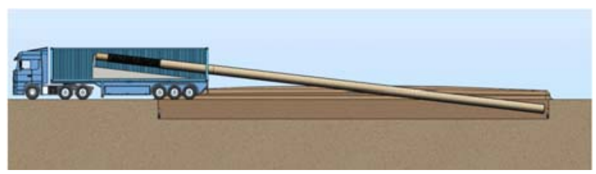


Fig. 3. Rendering of how the Mobile Manufacturing Unit (MMU) could create an FRP pipeline of virtually infinite length in the field.

A 5-10 m long mandrel (i.e. tube) is mounted on a trailer that can travel along the trench. The steps of the construction can be summarized as follows; the choice of carbon or glass fabric and the number of layers is a function of the design and loading requirements for the project:

a) A roll of carbon or glass fabric is saturated with epoxy resin using the on-board saturating machine and it is wrapped once or twice around a 7m length of the mandrel
b) A honeycomb panel is wrapped around the mandrel and if necessary spliced at the seams
c) Additional layer(s) of glass or carbon fabric saturated with epoxy resin is wrapped around the mandrel
d) The epoxy resin will start to harden in about an hour in ambient temperature; a slight heating of the mandrel can reduce this time to less than 10 minutes
e) The finished pipe is largely slipped off the mandrel, leaving a length of only 0.5 m on the mandrel
f) Steps a) through e) are repeated to build a continuous joint-free pipe
g) The finished pipe is sloped in the trench as the truck travels along the trench

A crew of 5 can easily manufacture 50 m of a 600-mm pipe by hand per 8-hour shift. It is anticipated that the Mobile Manufacturing Unit (MMU) will be able to produce around 500 m of pipe in a 24-hour round the clock operation. Thus, the MMU will significantly reduce manufacturing time and improve quality control.

5. TEST RESULTS

The development of InfinitPipe® has been financially supported by the U.S. National Science Foundation (NSF) through a grant from the Small Business Innovation Research (SBIR) program. In this 6-month long study, some of the pertinent characteristics of the pipe were evaluated to demonstrate if such a pipe was feasible to construct. Most of the tests were performed at the Trenchless Technology Center (TTC) of the Louisiana Tech University (Allouche and Alam 2014).

Samples of InfinitPipe® with an average outside diameter of 322 mm were manufactured at QuakeWrap facilities and they were shipped to TTC for testing. The construction of the pipe consisted of the following layers from inside towards the outside which resulted in an average thickness of only 9 mm:

- Two (2) layers of veil
- Single layer of QuakeWrap TU27C Unidirectional Carbon Fabric
- Single Layer of QuakeWrap TB20C Biaxial Carbon Fabric
- Single Layer of 8mm thick 3D Glass Fabric cut in a 6-inch wide band and helically wrapped around the pipe
- Two (2) Layers of QuakeWrap VB26G Glass Fabric

A variety of short-term tests were performed on these samples. Due to space limitation, only some of those results are presented here.

Stiffness - Five specimens with an average length of 305 mm were tested according to ASTM D2412 parallel plate test at a loading rate of 12 mm/min. Final deflection value was set to 30% of the inner diameter (90 mm) of the pipe. The load vs. deflection curves for all specimens are shown in Fig. 4. The behavior can be divided into three distinct regions. The moderate slope at the beginning (up to around 4 mm deflection) of the curve may be due to the result of initial adjustment of the load application mechanism. In the second segment, steep slope from around 4 mm to 19 mm shows elastic behavior of the sample. It was observed that for all the specimens the elastic relation exists between 4400 N to 6200 N. Beyond that, flat slope indicated failure and cracks in the specimen.

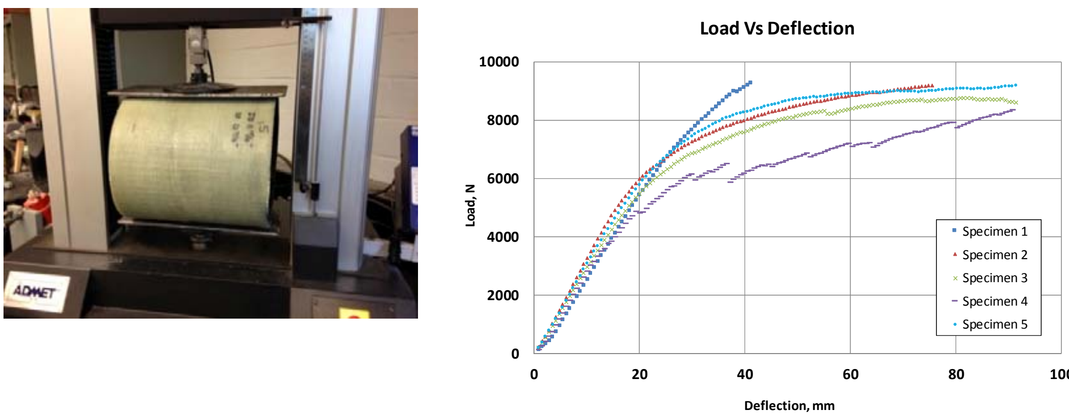


Fig. 4. ASTM D2412 test setup and load-deflection curves

The average stiffness factor and modulus of elasticity were calculated based on the 5% deflection, i.e. 5% change of the inside diameter. Average stiffness factor was found to be around 500 N-m and modulus of elasticity was above 6,900 MPa. Crack propagation was observed along the seam for most specimens at full deflection and the average modulus of elasticity value was calculated close to 5,500 MPa. Average stiffness at 5% deflection was found around 1 MPa while it reduced around 57% for full deflection. Ability of the specimens tested to resist overburden load is considered adequate for a wide range of practical applications.

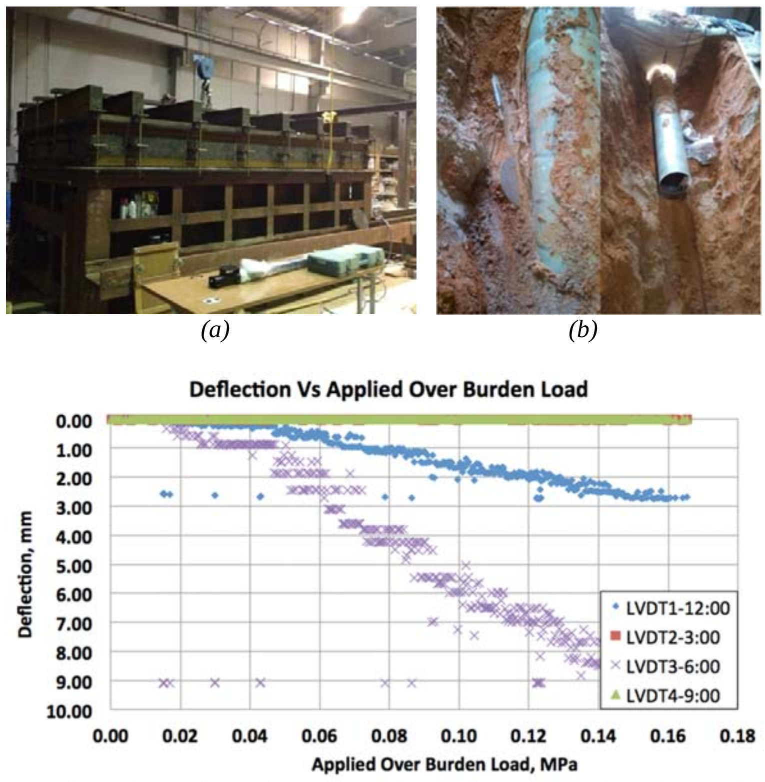
Impact Test – Ten 300-mm long specimens were cut from a 300-mm ID *InfinitPipe®*. Tests were performed at room temperature of 22°C. A Charpy impact test device, capable of measuring the energy absorbed by the pipe's wall when subjected to an impact load, was utilized. The impact head was replaced by a Tup Type B, as mentioned in ASTM D2444 (Fig. 5).

Fig. 5. Charpy impact test

The scale on the instrument was calibrated to measure the energy imparted upon the pipe's wall as a free swinging weight (pendulum) positioned at 120° to the pipe's wall, was released. The specimen was positioned and securely clamped or strapped to a platform bolted to the base of the Charpy. The weight was positioned at an angle of 120°, locked, and released. As the Tup hit the specimen, the gauge on the dial moved from 120 ft-lb to a reading which was interpreted as the energy absorbing capacity of the material. The average absorbed energy was found 162 N-m which is close to anneal steel. For anneal steel similar tests produced around 161.3 N-m.

Over Burden Pressure – The soil testing apparatus used in this test was 1.8 m wide × 3.6 m long and 1.5 m deep (Fig. 6a). On the opposite short walls of the soil box, two steel plates with 400 mm diameter circular openings were fabricated and slid through a pair of collars. The peripheral walls and the bottom of the soil box were covered with three layers of polyethylene sheets. Lubrication was applied in between the layers to ensure minimum friction between the soil and the chamber's walls. The soil box was filled with a 300 mm layer of SB2 soil (hard small rocks usually used for non-paved driveways), compacted each time using a single direction plate compactor at 150-mm layer, and covered with 150 mm of compacted silty-sand which reached the invert of the *InfinitPipe®*. Thus, minimum vertical global movement due to the applied over burden load was ensured, while a smooth surface at the invert of the pipe was provided.

Five earth pressure cells (EPCs) were placed in the vicinity of the pipe specimen ensuring uniform contact area with the surrounding bedding material. The soil box was filled with a 150 mm layer of silty-sand and compacted each time using the same plate compactor up to the inner edge of the soil box. After the soil box was filled to the top, a rectangular seal was glued to the top edge of the soil box, and a rubber bladder covering the seal was placed on top of the soil surface to ensure uniform pressure before the lead was placed. Various measures were taken and tested to ensure that the lid on top of the box was fully sealed and no leakage would occur (Allouche and Alam 2014).



(a) *(b)*

(c)

Fig. 6. Over Burden test: (a) test setup, (b) specimen exhumed at the end of the test, and (c) deflection vs. pressure response of the pipe

A frame supporting four (4) LVDTs was positioned inside the pipe. The LVDTs provided continuous information regarding the displacement of the *InfinitPipe®* pipe specimen at the invert, crown, and spring-line regions at the center location along the 4.27-m long pipe specimens. As shown in Fig. 6c, the data recorded by the LVDTs at positions 3 and 9 O'clock reveals no lateral expansion at the spring line of the *InfinitPipe®*. These are shown by overlapping series of data points at nearly zero deflection. LVDT1 located at the crown showed a maximum deflection of around 2.5 mm that is approximately 0.8% of the inner diameter. Readings obtained from LVDT1 were subtracted from those collected by LVDT4 located at the invert and showed around 6 mm of global settlement or rigid body movement of the pipe. Drop of the deflection readings after 2.5 mm deflection by LVDT1 and 9 mm deflection by LVDT4 are attributed to depressurization of the air bladder.

At the conclusion of the test, the pipe sample was exhumed from the soil chamber (Fig. 6b). The pipe remained in excellent shape with no visible damage.

Burst Pressure – The initial group of specimens that were constructed with two thin layers of epoxy-saturated veil as the inner surface were tested under external pressure to evaluate their buckling behavior. Those specimens started to leak at relatively low hydrostatic pressures. It is noted that those specimens were not designed for external hydrostatic pressure and in retrospect they may have performed satisfactorily if the uniform pressure were applied in a different manner. Nevertheless, since there were no specimens remaining for burst tests, an additional sample with a slightly new design was constructed.

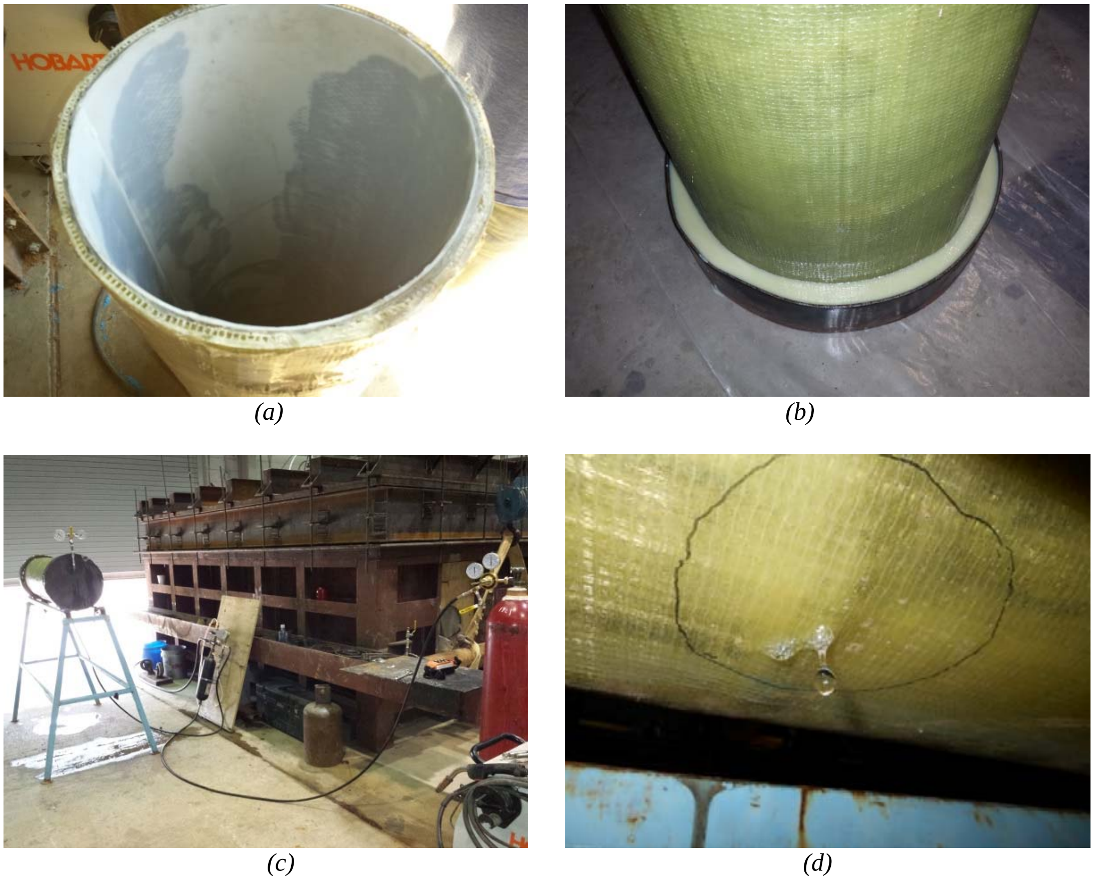


Fig. 7. Burst pressure test: (a) test sample. (b) end caps installed, (c) sample being tested, and (d) seepage of water through the pipe.

For the new specimen, the interior layer of the pipe consisted of a 3-mm thick High Density Poly Ethylene (HDPE) sheet that was formed into a cylinder by heat-fusing its edges to create a 300mm diameter by 1200 mm tube. This tube was then wrapped externally with the identical number of layers of epoxy-saturated carbon, 3D glass, and glass fabrics as the previous specimens (Fig. 7a). First, solid caps were fabricated with an inner and an outer circular flange, each 75 mm tall. Next, the specimen was suspended and positioned over the flange 12 mm to ensure free flow of polyurea. Polyurea was poured in between the outer flange and the pipe's outer wall, and it filled the gap between the inner flange and the pipe's inner wall (Fig. 7b).

The specimen was positioned on a metal frame and two ball valves were attached on the caps (Fig. 7c). The specimen was filled with water to bleed the inside air out. Two pressure gauges – one 0-7 bar and the other 0-200 bar were attached to the outlet. Pressure was applied on the specimen. Seepage through the specimen began when the internal pressure reached 5.5 bar and water drops became visible as water flew between the fiberglass and carbon fiber layers (Fig. 7d). Inspection of the specimen indicated that this leakage could be potentially attributed to a manufacturing defect in the welded edges of the HDPE tube. At this early stage of the technology development, all specimens including the welds were produced manually. As the production is automated and the Mobile Manufacturing Unit is developed, these issues will be addressed. It is noted, however, even at 5.5 bar, the current InfinitPipe® does have enough pressure rating to be used in many gravity flow projects such as sewer pipes or culverts.

6. FIELD APPLICATIONS

The development of the MMU that would allow continuous onsite manufacturing of InfinitPipe® is currently underway. The first prototype of this equipment will be completed by November 2014 and is capable of producing 200-mm diameter pipes. This effort will continue for larger diameter pipes and will encompass further improvements with the pending financial support through the NSF Phase II SBIR grant. In the meantime, smaller lengths of the pipe that can be made by hand are being manufactured for slip-lining projects. This pipe known as StifPipe® has been used on two projects that are described below; the product is also under consideration for other projects in the U.S. and Australia.

Gravity Flow – The first application of this technology was for slip-lining a 600-mm corrugated metal pipe culvert near Mobile, Alabama (Fig. 8). The 20-m long culvert was covered with about 1.5m of soil and it was corroded. Due to access requirements, the client preferred short segments of the pipe, around 2.5 m long. Because the pipe was not subject to any internal pressure, a glass fabric was used in lieu of carbon fabric to lower the cost. The construction of the pipe starts by using a 457-mm diameter by 6-m long sonotube as the mandrel. The outer surface of the sonotube is covered with a mold release to allow easy removal of the finished pipe. Two layers of a biaxial glass fabric were saturated with epoxy resin and wrapped around the mandrel. A 25mm thick Polypropylene Honeycomb was then wrapped around the mandrel, making sure all the joints were butted properly to eliminate any points of weakness in the pipe. This was followed by wrapping two additional layers of the same resin-saturated biaxial glass fabric around the honeycomb. The resin system used for this case cures in several hours at ambient temperature and it is ideal for such applications where there is no particular race against time to strip the pipe from the mandrel.

Fig. 8. Slip-lining a corroded culvert in Mobile, Alabama with StifPipe®: (a) glass fabric layers wrapped around the mandrel, (b) manufactured pipe segments prior to shipment, (c) view of the job site, (d) light-weight pipes being connected and slipped into the culvert by hand, (e) culvert partially slipped, and (f) finished repair

Due to site access limitations, the pipe segments were built in 2.4-m long segments. A slightly larger diameter StifPipe® of the same design was built and cut into 300-mm long couplers to connect the pipe segments together (Fig. 8b). Each pipe segment weighs only about 25 kg; this low weight eliminates the need for heavy lifting and jacking equipment during the installation. The individual pipe segments are connected together in the field and pushed into the host culvert; no de-watering of the culvert is required at this stage (Fig. 8e). The annular space between the StifPipe® is filled with grout leaving a smooth pipe in place (Fig. 8f).

Pressure Pipe – In another application, 7 steel pipes each 1220-mm in diameter and 1.2 m long in Avalon Pumping Station in Carson, California were severely corroded. These pipes carry potable water at a pressure of nearly 10 bar. Each of these 7 pipes corresponded to a pump outlet pipe. The client was interested in maximizing the flow through these pipes.

A fully adjustable mandrel such as the one shown in Fig. 9a can be used. The telescopic arms of this mandrel can be pushed towards or away from the center, allowing for a continuous range of diameters. The construction of the pipe used two layers of carbon fabric on the inside to resist the internal pressure. A 9.5-mm thick honeycomb core and two layers of glass fabric were also used. The finished pipe had a thickness of about 14 mm. But more importantly, the StifPipe® was custom designed so the outside diameter was 1205 mm, leaving a very small annular space that was filled with resin in the field. As shown in Fig. 9c, this resulted in little loss of diameter and flow capacity in the pipe. It is also noted that StifPipe® is certified under NSF-61 for repair of potable water pipes.

The mandrel shown in Fig. 9a can be easily modified by moving the arms towards or away from the center to create a non-cylindrical pipe of desired shape. This has significant applications in repair of many old culverts and sewer pipes with arch, oval or other shapes, where slip-lining with a cylindrical pipe could result in substantial loss of flow capacity.

(a) *(b)* *(c)*

Fig. 9. Slip-lining corroded Steel pipes in Avalon Pumping Station, Carson, CA with StifPipe®: (a) adjustable diameter mandrel, (b) pipe segments prior to shipment, (c) finished repair showing a snug fit with between the StifPipe® and the host pipe

7. FUTURE PLANS

Once the MMU is complete, it is envisaged that InfinitPipe® will be a very cost-effective pipe for a wide range of applications. One application is for slip-lining culverts under roadways. There is a large inventory of corroded culverts worldwide. By setting the MMU in front of the culvert, as the InfinitPipe® is produced and comes off the mandrel, it is pulled into the host culvert with a winch. The light weight of the pipe makes this operation very easy. The annular space between the InfinitPipe® and the host culvert can be filled with grout.

Construction of new sewer pipes is another application. Connections of laterals to this pipe can be achieved using commercially-available fittings as shown in Fig. 9. At the same time, the design of the pipe easily allows for increasing the pressure rating of the pipe by adding one or more layers of carbon fabric to the inner layer of the pipe. This combined with existing NSF-61 certification, makes the pipe an ideal candidate for water pipes. Segments of InfinitPipe® can be joined together in the field by a wet layup system, where two pieces of pipes are externally wrapped with Carbon FRP fabrics saturated with resin. Similar approach is utilized in fiberglass pipes in the gas industry (ADTECH 2009a and 2009b).

While the initial focus will be on the low and medium pressure applications, InfinitPipe® can be easily designed to withstand higher pressures. The internal number of layers of carbon fabric are designed based on the pressure of the pipe. Each layer of carbon fabric adds only about 1 mm to the pipe thickness and little to the weight of the pipe, but it results in significant increase in the ability of the pipe to resist internal pressure.

Perhaps one of the largest market for InfinitPipe® in the initial years is in mining and gas fields where there is growing need for water pipes. These industries seem to be more open to embracing innovative technologies that deliver faster and more economical alternatives. They also often lack the stringent requirements imposed by public agencies such as municipalities and water districts, which delay the acceptance of new products such as InfinitPipe®.

Fig. 10. Installation onto InfinitPipe® of a lateral connection made by Inserta Tee®

Another advantage of this technology is its mobility that allows construction of pipelines in remote and inaccessible locations. Whether it is for oil and gas exploration or for drinking water, the technology can offer unique opportunities for many developing nations. In fact, the StifPipe® or InfinitPipe® technology can be implemented by local villagers to build pipes and storage tanks to meet their drinking and agricultural needs.

One of the concerns about InfinitPipe® is the ability to monitor the health of the pipe during its service life. We have initiated a non-destructive testing program with colleagues at the University of Arizona to detect defects in the pipe by inspecting the pipe from the inside only. The initial results are very promising and the ultrasonic waves have successfully identified defects in curved plate segments that were removed from pipe samples.

InfinitPipe® weighs much less than conventional pipes and the delivery of the raw materials to the job site reduce the transportation needs greatly compared to shipping finished pipes from the factory. The FRP products used in the pipe do not corrode and thus no cathodic protection is needed. The elimination of the joints prevents leakage and promotes a cleaner environment. The pipe can be constructed in a short time and with a small crew of workers. When all these factors are considered, it is obvious that if successful, InfinitPipe® will be the world's first "Green and Sustainable" pipeline technology.

8. ACKNOWLEDGEMENT

The experimental study reported in this paper was performed based on NSF SBIR Contract No. 1315561. The author acknowledges the financial support provided by NSF. However, the views presented here are those of the writer and not NSF.

9. REFERENCES

ADTECH FRP Pty Ltd. 2009a. "ADTECH Project Completion Report," June 2009.

ADTECH FRP Pty Ltd. 2009b. "ADTECH Project Completion Report for Eastern Star Gas – Bibblewindi Flowline 32,500m," June 2009.

Allouce, E, and Alam, S. 2014. “Experimental Evaluation of Newly Developed InfinitPipe®,” Trenchless Technology center, Louisiana Tech University, July 2014, 33 pp.

Baker, A., Dutton, S., and Kelly, D. 2004. *Composite Materials for Aircraft Structures*, 2nd Edition, American Institute of Aeronautics and Astronautics

Ehsani, M.R. 2012. “Introducing A New Honeycomb-FRP Pipe”, *ASCE Pipelines Conference*, Miami, FL, August 2012.

Ehsani, M.R. and Pena, C. 2009. "Rehabilitate Pipelines with Minimal Downtime," *Opflow*, American Water Works Association, Dec. 2009, 22-25.

ICRI. 2008. “Restoration of Large Diameter Prestressed Concrete Cylinder Pipelines”, Award of Excellence in Water Structures Category, Concrete Repair Bulletin, ICRI, Nov/Dec 2008. Pp. 45-47.