How to Manufacture an Endless Pipe Onsite

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ABSTRACT

Pipelines have been traditionally constructed in short 20-40 feet (6-12 m) long segments. The pieces are shipped from the factory to the job site and stored on site until they are joined together. This process leads to delays in projects due to the time required to build the pipe segments, and high transportation charges for delivery of the pipes to the job site. Once connected, the joints are a major source of leakage and maintenance expense that continue for the life of the pipeline. The pipe materials require protection against corrosion and the heavy weight of the pipes is a safety concern, making pipeline construction one of the most dangerous trades.

In view of the above limitations, the author has developed an onsite-manufactured pipe that allows construction of a virtually endless pipe of any diameter and pressure rating onsite. Unlike conventional pipes, the walls of this pipe are made of a lightweight core that is encapsulated between layers of Carbon or Glass Fiber Reinforced Polymer (FRP). The thickness of the core and the number of layers and type of fibers, i.e. carbon or glass, are determined based on the project loading requirements

This paper focuses on the development of the first prototype of the Mobile Manufacturing Unit (MMU) that was completed in October 2014. Within the MMU, layers of resin-saturated fabrics are wrapped around a mandrel and cured to create the pipe. As the MMU travels along the roadway, it produces a continuous pipe at a rate of 2 miles (3 km) per week. Various aspects of the MMU that were considered and the lessons learned as part of this R&D are presented. A hand-made version of this pipe can be produced with minimal equipment, providing safe drinking water to remote sites and villages worldwide.

INTRODUCTION

Construction of pipes with available technology 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 20 feet (6 m) or so. These joints are a potential source of leaks, which can inflict significant loss of revenue as well as harm to the environment. For treated water, the problem is so prevalent that the term Non-Revenue Water (NRW) has been globally accepted to refer to the treated water that is lost primarily through leaks. According to a World Bank report, the cost of NRW in 2006 was conservatively estimated at $14 billion (Kingdom, et al. 2006).

For the energy sector, the recent surge of exploration and development of shale gas has increased the demand for pipelines significantly. The Houston Chronicle (Mello 2013) has reported that a shortage of qualified welders has delayed construction of pipelines. The rapid escalation of energy production in shale formations across the U.S. has produced a bonanza of oil, but it has left many states scrambling to handle the natural gas that often flows in large volumes along with the crude. According to a recent article in the Los Angeles Times, the amount of gas flared in the Bakken oil field in North Dakota has nearly tripled since 2011, sending gas worth more than $1 billion a year into the sky (Dave 2014). The primary reason for this waste of energy is the inability to build pipelines quickly.

For large diameter pipes, the transportation costs alone from the plant to the job site add significant expense to the project. Moreover, handling of large pipes is a high-risk task. According to OSHA's records, there were 19 deaths in 2013 in pipeline construction projects; most occurring when the pipes are being loaded onto or unloaded from the trucks or when the pipe is being placed in an open trench (OSHA Fatalities and Catastrophes Report FY2013).

It is our firm belief that the current method of pipe manufacturing is very inefficient and unsustainable; it is only a matter of time before technologies will be developed for on-site manufacturing of pipes. This paper presents one such solution and the lessons that we have learned in pursuit of such a goal.

EARLIER DEVELOPMENTS

In response to the above challenges we started the development of a lightweight honeycomb-FRP pipe that was introduced recently (Ehsani 2012). That pipe (called StifPipe®) uses a similar technology but it is made *by hand* in shorter segments for use in repair of pipes by the slip-lining method. A typical pipe could be constructed according to the following steps:

1. Provide a reusable and easily collapsible mold or mandrel to match the shape and size of the pipe being manufactured; it is best if the mandrel is designed such that its diameter can be adjusted in continuous or small increments;
2. Wrap one or more layers of resin-saturated carbon or glass fabric by hand around the mandrel; the number of layers and type of fiber (carbon or glass) will be determined by our design engineers based on the project pressure requirements;
3. Wrap a layer of a honeycomb sheet on top of the fabric layers;
4. Wrap additional one or two layers of resin-saturated glass fabric by hand around the mandrel;
5. Allow the pipe to cure in ambient temperature (about 12 hours);
6. Collapse the mandrel and remove the finished pipe segment from the mandrel.

This process is fairly simple and we have used it to build pipe segments for repair of gravity and pressure pipes. A 60-ft (18 m) long 24-inch (610mm) corrugated metal culvert was repaired in Mobile, AL (Ehsani 2013) (Fig. 1). To keep the cost down, this pipe was made with glass fabric only. In another application, shown in Fig. 2, seven segments of 4-ft (1.2m) long 48-inch (1220 mm) diameter corroded steel pipes in Avalon Pumping Station, Carson, CA were repaired with this technique (Ehsani and Parsons 2013). The custom pipe segments were manufactured with an outside diameter of 47 inches (1194 mm), to minimize the loss of flow capacity after the repairs. To meet the operating pressure requirements of the plant, this pipe used two layers of carbon FRP on the inside plus two layers of glass FRP as the outer surface.

While the above procedure works perfectly well, its main shortcoming is the speed of construction. These pipe segments are intended to be built in short pieces prior to installation using the slip-lining technique. They require several hours for the pipe to cure on the mandrel. These limitations had to be overcome for an onsite manufactured pipe.

Figure 1. Honeycomb-FRP pipe being made on a mandrel for repair of culvert.

Figure 2. Making and installation of honeycomb-FRP pipe used for repair of pressure pipe.

CONTINUOUS PIPE MANUFACTURING

Considering the relative ease of manufacturing of this pipe, it would be a major achievement if the manufacturing process could be automated to build the pipe in a continuous manner in the field at a fast rate of production. However, to make this transition successfully, there are several design and manufacturing issues that need to be addressed. Each of these challenges are discussed in more detail below.

Mandrel: The mandrels that we had used had a fixed diameter (Fig. 1) or they required access to the inside of the mandrel to collapse the mandrel and remove the finished pipe (Fig. 2). The automated system must include a mandrel that can be automatically collapsed without access to the inside of the mandrel. One possible design is shown in Fig. 3. The mandrel is made of a tube with a slit along the length. Turnbuckles or electrically-controlled links can be used to reduce the diameter of the mandrel slightly, allowing the finished pipe to be removed. A small overlapping flap along the length of the mandrel can be used to cover the gap that is created by the slit. The mandrel will be supported as a cantilevered arm from one end (Fig. 7b). The finished pipe will come off of the unsupported end of the mandrel (Fig 7a). The operator can control the opening and closing of the mandrel with the switches shown in Fig. 7b.

Figure 3. Collapsible mandrel

Surface Finish: A major feature of the mandrel has to be a non-stick surface so that when resin-saturated fabric is cured on the mandrel, it could easily be removed. There are hand-applied or sprayed coatings that can be applied to the surface of the mandrel but these require a fresh application every time a new segment of pipe is being made. This would increase the production time. Other coatings such as Teflon or Mylar sheets can be used also. However, most of these coatings cannot stand the heat that is required for the curing of the FRP. There are similar coatings that could withstand the heat, but these too may not last the full life of the mandrel and periodical re-coating may be necessary. The best solution is a chrome-plated plate. The smooth surface of such a finish is virtually free of any non-uniformities and would allow easy removal of the finished pipe. At the same time, the chrome finish can easily handle the heating of the mandrel during the curing process.

Epoxy: The speed of manufacturing a pipe on site is greatly influenced by the properties of the epoxy being used. The pipes shown in Figs. 1 and 2 were made using a QuakeWrap epoxy which is part of a proprietary system that meets the strict NSF-61 standards for potable water pipes. The resin fully cures in 24 hours in ambient temperature (Epoxy A in Fig. 4). While this feature (i.e. requiring no special curing process) is ideal for repair of pipes and large walls or slabs in a building, the long cure time delays the speed of manufacturing new pipes. Typically, it will take less than 2 minutes to wrap the fabric layers around a 10-ft (3m) long mandrel; after which laborers would have to *wait* while the epoxy cures before removing the finished pipe. Epoxy cure time is the major bottleneck in the production process, so any reduction in this time will significantly impact production speed.

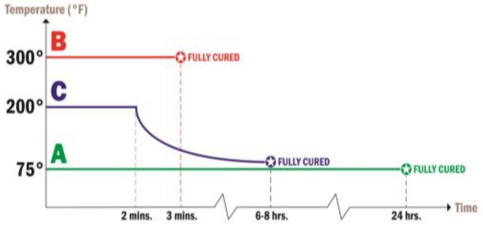

Figure 4. Temperature vs. cure time for epoxies.

After a number of trials and consultations with industry partners, a new resin was selected that fully cures in only 3 minutes if heated to 300F (150C) (Epoxy B in Fig. 2). A further advantage of this resin is that it has a long pot life at ambient temperature. Rolls of fabric can be saturated with resin a day before they are needed. The saturated fabric rolls can be stored next to the MMU in the field and loaded into the MMU to be wrapped around the mandrel. This eliminates the need for mixing resin and saturating fabric in the field, a time-consuming process.

A third category of epoxies shown as Epoxy C in Fig. 2 offer two potential advantages. These epoxies require a shorter time (2 min. vs. 3 min.) and less heat (200F vs. 300F) or (93C vs. 150C) to start the curing process. Once the pipe is removed from the mandrel and the heating source, the pipe will continue to cure at ambient temperature for a few more hours until it is fully cured. Because the pipe is not going to be subjected to any internal or external loads immediately, this type of epoxy appears to be the most advantageous for on-site pipe manufacturing.

Heating Source: As discussed earlier, the epoxy must be heated to initiate the curing process. Several techniques for heating the resin were explored and tested. These included LaminaHeat™ (Fig. 5) which is connected to an electrical circuit and provides a very uniform heated surface. However, because of the time required to raise the temperature in LaminaHeat™ to 300F (150C), it was ruled out. Another promising technology is Variable Frequency Microwave (VFM) by Lambda Technologies (Morrisville, NC) that claims an efficient uniform curing of the resin. Unlike conventional microwave ovens used at homes that operate at a fixed frequency (primarily to excite water molecules), this technique varies the microwave frequencies to ensure that all parts of the subject are heated at the same rate. Samples of fabric and resin were made into a pipe sample cured with VMF in one of Lambda Tech’s ovens. The sample looked very good and the epoxy was fully cured. However, a VFM oven based on this technology to fit a pipe would cost around $100,000. For that reason, this option was ruled out for the time being.

A third system tested was a technology where carbon nanotubes are dispersed in a resin to create an electrically conductive resin. Applying a film of this resin to the inside surface of the mandrel and passing a current through it generates heat that in turn heats the mandrel and the inside layer of the pipe. This technology is viable since the resin bonds to the surface of the mandrel and stays in place (unlike a separate heating film or element that may come apart from the mandrel). The disadvantage is that the resin must be applied manually to the inside surface of the mandrel; making it difficult to apply to smaller diameter mandrels.

Figure. 5. LaminaHeat and propane heater tried in curing the pipe.

To prevent delays in the project, a decision was made to use gas heaters to heat the resin (Fig. 5). For testing purposes, a temporary enclosure was built and the pipe samples were placed inside this enclosure. The pipe was heated using gas heaters both inside and outside the pipe. While this system worked well, it does require supply of propane on the MMU platform. For some remote sites, this could result in additional challenges. For that reason, the use of propane was ruled out.

The heating element used in the first MMU is shown in yellow color in Fig. 7b. This is a clam-shell shaped insulated box that includes electrical heating elements and small fans to circulate the heated air once the shell is closed around the pipe. For the first MMU, the pipe is being heated only from the outside. Considering the diameter of the mandrel for the first MMU 8 in. (200 mm), heating from the outside was sufficient to cure the pipe. As the diameter of the pipe increases, the MMU must be modified to heat the pipe from both inside and outside. The resin/carbon nanotube option discussed above offers a great solution for heating the pipe from inside when larger pipes are being made and the large diameter of the mandrel allows application of this resin.

Interior Finish: Water tightness of the pipe is of course very important. As part of the NSF SBIR Grant, short term hydraulic burst tests were conducted to determine the pressure rating of the pipe (Ehsani 2014). The interior surface of those test pipes were made of two thin sheets of glass veil saturated with resin, the hypothesis being that this combination would create an impervious watertight layer. Tests showed that those specimens started to leak at relatively low pressures (less than 10 psi) due to water seeping through the veil.

Two additional pipe samples were made where a ⅛" (3mm) thick HDPE sheet was wrapped around the mandrel and the edges of this sheet were heat-welded together to create a thin HDPE pipe on the mandrel. Carbon and glass fabric were then wrapped on the outside of this thin HDPE pipe. The result was basically a thin HDPE pipe that derived stiffness and strength from the external FRP layers. A further advantage of such a pipe is that the interior HDPE layer does not bond to the mandrel (unlike a resin-saturated fabric), so removing the finished pipe from the mandrel is much easier. Furthermore, HDPE pipes manufactured in the U.S. by companies such as JM Eagle have been used extensively as water or sewer pipes.

After numerous attempts at creating a good weld at the seams of the HDPE, the pipe samples were made and tested at the Louisiana Tech’s Trenchless Technology Center. This sample resisted an internal pressure of 80 psi (5.5 bar) at which time a pinhole in the welded seam of the HDPE started to leak. This leak developed because of poor workmanship. 80 psi (5.5 bar) is more than sufficient for many projects that operate under gravity flow (e.g. culverts and sewer pipes). Improving the quality of the weld will delay or eliminate this mode of failure. However, the welding of the HDPE and automating this process may be too difficult to achieve in the near future. Using one or two layers of chopped glass mat richly saturated with resin will provide a watertight internal surface for the pipe.

Connections and Fittings: The onsite-manufactured pipe described here is best suited as a transmission pipeline where few valves or fittings are needed. However, there will be a need for long segments of the pipe to be connected together. The ends of the pipe can be cut flush and two pipe segments can be externally wrapped with resin saturated carbon or glass fabric to create a longer pipe. Such connections are commonly used in assembly of fiberglass pipes and can produce pressure-rated fittings.

While our focus has been on manufacturing the long barrel of the pipe, elbows and fittings can be built by hand using the same technology as we have used to build shorter pipe segments (Figs. 1 and 2). Moreover, steel or fiberglass flanges and fittings from other manufacturers can be inserted into our pipe and secured with the wet layup system; these flanges can then be bolted together by conventional ways.

For sewer pipe or pipes with low operating pressure, many such products are readily available on the market. As shown in Fig. 6, Inserta Tee® provides a three-piece lateral connection consisting of a PVC hub, rubber sleeve, and stainless steel band that can be easily installed on InfinitPipe®. The connection shown here uses a compression fitting and is suitable for gravity flow pipes. Connections and fittings for water and other pressure pipe applications require further development. If necessary, the connection can be externally wrapped with FRP wet layup to increase its pressure rating.

Figure 6. Installation onto InfinitPipe® of a lateral connection made by Inserta Tee®

MOBILE MANUFACTURING UNIT (MMU)

The first prototype of the Mobile Manufacturing Unit (MMU) was completed in October 2014 (Fig. 7). The unit is only 28 ft (8.5 m) long and weighs less than 7000 pounds (3200 kg), so it can fit in a standard container for shipment to the job site. The lightweight MMU can also be mounted on a flatbed trailer and pulled with a small truck in areas where no developed road infrastructure exists.

One operator controls the entire equipment through the switches that are installed new the right end (Fig. 7 b). Rolls of glass or carbon fabric are saturated with resin in advance. A typical roll is 12 inches (300 mm) wide x 100 ft (30 m) long. The rotating hub shown on the left end of the MMU has arms where these saturated rolls are installed. The angle of orientation of these arms can be easily adjusted, resulting in different pitches for the fabrics being wrapped around the mandrel.

The pitch angle and speed of rotational and translational movement of the hub are set by the controls on the right end. As the hub rotates, layers of fabric are wrapped around the mandrel. The hub then comes to a halt, and the heating oven automatically rises and clamps around the recently wrapped fabric. The oven is heated and within three minutes the pipe is fully cured. The operator then collapses the mandrel, and the finished pipe is pushed out to the left, leaving only a small portion of the pipe on the left tip of the mandrel. The process of wrapping starts again, by continuing at the end of the previously completed pipe. This procedure can continue forever creating an endless pipe.


(a) (b)

Figure 7. Views from the (a) left and (b) right ends of the first prototype of the Mobile Manufacturing Unit (MMU)

A video of the MMU is available on YouTube and can be watched at this link (http://goo.gl/2KAzuD). In this demonstration video, an 8-inch (200 mm) diameter pipe is being built. The operation is stopped after 12 ft (3.6 m) of pipe has been made. The pipe has a pressure rating of 500 psi (34 bar) and weighs less than 2.5 pounds/ft (3.5 kg/m), allowing for easy handling (Fig. 8). The pipe is rigid enough to allow a truck driving over it without damaging the pipe even when the pipe is not embedded in soil. The MMU can produce pipe at a rate of 2 miles (3 km) per week.

Figure 8. First sample of onsite-manufactured pipe is very light and easy to handle.

The pipe can be either buried directly in a trench or it can be used to slip-line existing pipes. The method of manufacturing of this pipe is so versatile that allows the designer to change the design along the length of the pipeline. The pressure rating of the pipe is determined by the number of inside layers of carbon FRP fabric that are positioned in the hoop direction. As shown in Fig. 9, for example, when a pipe moves along a steep hill, the number of layers can easily be reduced as the pressure in the pipe is reduced due to change in elevation. Similarly, when a portion of the pipe has to span a crossing, additional layers of carbon can be applied in the longitudinal direction to increase the flexural strength of the pipe – acting as a beam.

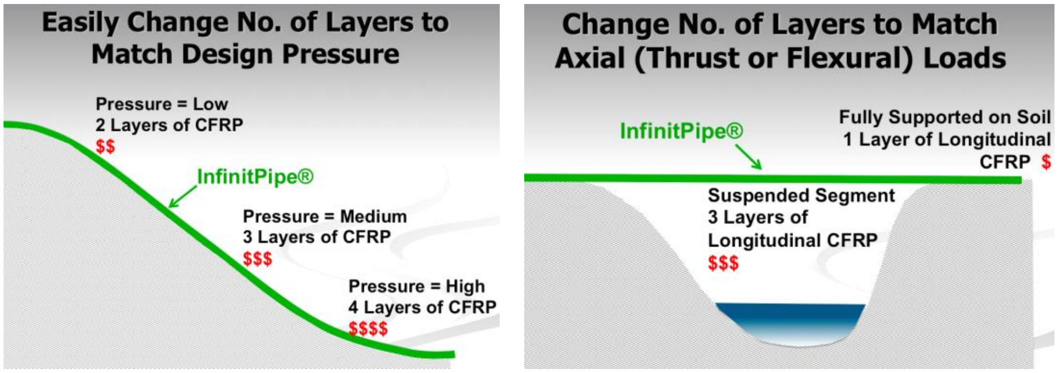

Figure 9. Design of onsite-manufactured pipe can be easily changed to accommodate changes in stresses along the pipeline.

The overall stiffness of the pipe can similarly be modified. For example, for slip-lining a subsea pipeline, it is possible to make a very strong yet semi-flexible pipe that can be pulled into the host pipe as the pipe is made on shore. Such a liner can be designed to accommodate the sweeping angle changes that may be present in the host pipe. Yet the liner/pipe is so light that it will be nearly buoyant in water, requiring little jacking force to pull it into the deteriorated host pipe. We have been contacted by a few clients for such retrofit applications.

CONCLUSIONS

The results of a long term R&D process by the author has led to the development of a new type of pipe that can be manufactured onsite in an endless fashion. The lightweight pipe is non-corroding and can be designed to resist any internal pressure. The unique use of the materials make this pipe very economical. Depending on the diameter of the pipe, one container of raw materials can be shipped to produce over a mile of pipe in a remote site.

While the first prototype of the Mobile manufacturing Unit has been developed and is operational, there are many improvements that can be made on this model. Nevertheless, there is little doubt that such a technology can revolutionize the pipeline manufacturing industry by reducing cost and delivery time, while producing a non-corroding pipe with few joints to leak.

ACKNOWLEDGEMENT

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