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Australia's Outback Offers Fertile Ground to Introduce New Culvert Repair Technology

Mo Ehsani, Professor Emeritus of Civil Eng., U. of Arizona, and President, QuakeWrap, Inc., Tucson, AZ USA
Stephen Day, Principal, Stephen Day and Associates, Cairns, QLD, Australia
Tony White, Business Development Manager, QuakeWrap Australia, Yeronga, QLD, Australia

1. Abstract

Steel corrugated metal pipes (CMP) used in construction of culverts often corrode, resulting in reduced load rating for the culvert. Slip-lining the culvert with a smaller diameter pipe has been successfully used worldwide. However, when the site is remote, the transportation charges and the need for heavy jacking equipment add significant cost to such repairs.

This paper describes the development of a new type of sandwich Fiber Reinforced Polymer (FRP) pipe for slip-lining culverts. The pipe can be made on site or very close to the site to minimize transportation costs. Various layers of glass FRP are wrapped around a lightweight honeycomb core to create a rigid pipe of any shape or size. The product named StifPipe® received the 2016 American Society of Civil Engineers (ASCE) Innovation Award as the world's first green and sustainable pipe.

Although the pipe was developed in the U.S., Australia was the first country to embrace this technology on a major culvert repair project. 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 custom-made pipes manufactured in Australia were less than 1 inch thick and had an outside diameter of 51 inches. The lightweight pipe 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.

2. Introduction

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.

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 (Fig. 1). 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.

Fig. 1. Project Site in north eastern Australia

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.

3. 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.

Considering the above parameters, several conceptual treatment options were examined, with four identified as viable candidates for more detailed consideration. These repair alternatives are briefly described below.

The first option was to install a new structural concrete base to “bridge” the corroded section in the invert of the culvert. This option would be fairly low cost and the solution would provide a moderate life expectancy (20-30 years). The base would need to extend to mid wall (180 degree internal angle) which had not previously been done in Australia, and would require significant investigation and design to check the viability of the design and to obtain the necessary approvals.

The second option was to reline the entire culvert with a reinforced concrete pipe. The design and construction of such pipes are fairly simple. The cost of the pipe would be moderate and the repair would be durable, with a life expectancy of at least 50 years. Fire resistance of concrete is excellent, so there would be minimal risk due to fire damage. This repair could also be performed with minimal disruption to the travelling public. Even with some jacking of the culvert to reduce some of the ovality, the largest size concrete pipe that could be utilized would be one with a 1350 mm nominal ID. A Class 4 pipe will have an ID of 1314 mm (51.7 in.) and a wall thickness of 105 mm

(4.13 in.). These pipes are supplied in 2.44 m (8.0 ft.) lengths with each segment weighing about 6200 pounds (2800 kg). The project would have required 10 pipe segments and a jack and reaction frame to push the pipe segments into the culvert. This would add significant cost to the field installation. Moreover, this option would result in 44% loss of cross section, resulting in increased afflux and outlet velocity.

The third option was to reline the pipe with a self-supporting 1500 mm (59 in.) Fibre Reinforced Polymer (FRP) pipe liner. The new sandwich construction pipe, named StifPipe®, is made of non-corroding materials and has an expected service life of 50 years. The relatively simple installation could be completed in 5 days at a moderate cost. The lightweight pipe eliminated the need for jacking equipment to push the pipe segments into the culvert. If desired, the pipe could also be manufactured to an oval shape to match the shape of the deformed culvert. Installation could be carried out during the wet season. The waterway area loss would be only 35% with increased afflux and outlet velocity. Some velocity dissipation would be required at the outlet, but the increased afflux would not affect local buildings. Although there is some risk of damage to the pipe during a fire event, in this instance, the risk was assessed to be low for this site. Lastly, although DTMR had no prior experience with this product, considering its potential use in other future projects, there was an interest in trialling this new technology.

The fourth option was to replace the culvert with a new 1800 mm (71 in.) reinforced concrete pipe. This does offer a long service life of 50 or more years. However, the project would require either road closure or construction of a side track, and significant excavation and earthworks. A long construction time would increase the risk due to wet weather and the disruption to traffic would be significant. Furthermore, the environmental impact could be severe and the permitting requirements more onerous. All of these factors and the high cost of construction weighed negatively against this alternative.

After considering all options, StifPipe® was selected due to:

- the low impact on traffic during installation
- the lower loss of waterway compared to other liner options
- the speed and ease of installation using light equipment requiring only minor access construction and having very low environmental impacts
- the potential to carry out the works during moderate rainfall events and with a relatively low lead time.

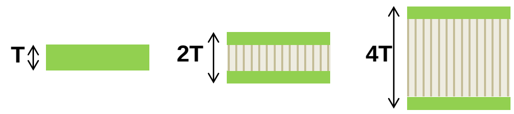
The other secondary factors that contributed to the selection of this pipe included the opportunity to trial a new product for possible use in other locations, particularly in remote areas of Far North Queensland, and the opportunity to utilize the organisation's direct labor workforce for installation of the product.

4. StifPipe®

The pipe used on this project has been recently developed by one of the authors (Ehsani 2012). 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 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 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.

A typical layer of carbon FRP fabric is about 0.05 in. (1.3 mm) thick. Placing two layers on top of one another results in a total thickness T = 0.1 in. (26 mm). However, as shown in Fig. 2, when these same two layers are separated by a 0.3 inch (7.6 mm) thick honeycomb, making the total thickness 0.4 in. (10 mm), 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.



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

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

StifPipe® weighs 10%-15% of a conventional fiberglass pipe, and significantly less when compared to steel or concrete pipes. 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.

All of 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). In addition to the gravity flow culvert repair presented here, the pipe has been used to repair pressure pipes in the U.S. and Puerto Rico (Ehsani and Cortes 2017).

5. Design and Construction of the Pipe

The liner was required to conform to relevant structural design criteria in the following documents:

1. The Australian Bridge Design Code (Australian Standard AS5100)
2. DTMR Document "Design Criteria for Rehabilitation of Circular Corrugated Metal Culverts"

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) (3.66-3.96 m)

A field survey was conducted to measure the exact dimensions of the deformed culvert. The diameter ranged between 64 to 71 inches (1620-1800 mm). Considering a pipe size that could be easily pushed through the culvert while leaving an adequate annular space for placement of grout, it was decided to build a StifPipe® with an outside diameter of 59 inches (1500 mm). The ability to build this pipe to virtually any desired shape and size is a major advantage of StifPipe® that allows maximum use of the available space and reduces loss of flow capacity. In this case, the 1 in.(25 mm) thick wall of the pipe resulted in an inside diameter of 57 in. (1448 mm) 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 (6.10 m) long; these would be sufficient to line the 80-ft (24.4 m) long culvert. Because StifPipe® is a recently developed concept in pipeline design, there are no industry guidelines 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 StifPipe®. Experimental studies on the behavior of this pipe that were conducted at the Louisiana Tech Trenchless Technology Center (Allouche and Alam 2014), and presented at the No-Dig Conference (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 interior 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.(8 mm) 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. (8 mm). This results in a rigid and lightweight structure.

The design of the StifPipe® for this project is shown in Fig. 3. 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. (25 mm).

Table 1. Properties of fabrics saturated with epoxy resin tested according to ASTM D3039

Fabric Type	**VB26G**		**VU27G**	
	US Units	SI Units	US Units	SI Units
Aerial Weight Fabric Only	26 oz/yd^2	880 g/m^2	27 oz/yd^2	915 g/m^2
Ply Thickness	0.040 in.	1.02 mm	0.05 in.	1.3 mm
Longitudinal (0°) Direction:				
Tensile Strength	54 ksi	373 MPa	85 ksi	587 MPa
Tensile Modulus	3,217 ksi	22.18 GPa	3,980 ksi	27.4 GPa
Ultimate Elongation	2.1%	2.1%	2.3%	2.3%
Breaking Force	2,170 lb/in	380 N/mm	3490 lb/in.	610 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	---	---

Construction of the StifPipe® begins by making a 22-ft (6.71 m) 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. 4). A thin sheet metal is wrapped around the ends of the telescopic arms to complete the mandrel. The outer surface of this sheet metal is coated with a debonding material to allow easy removal of the finished pipe.

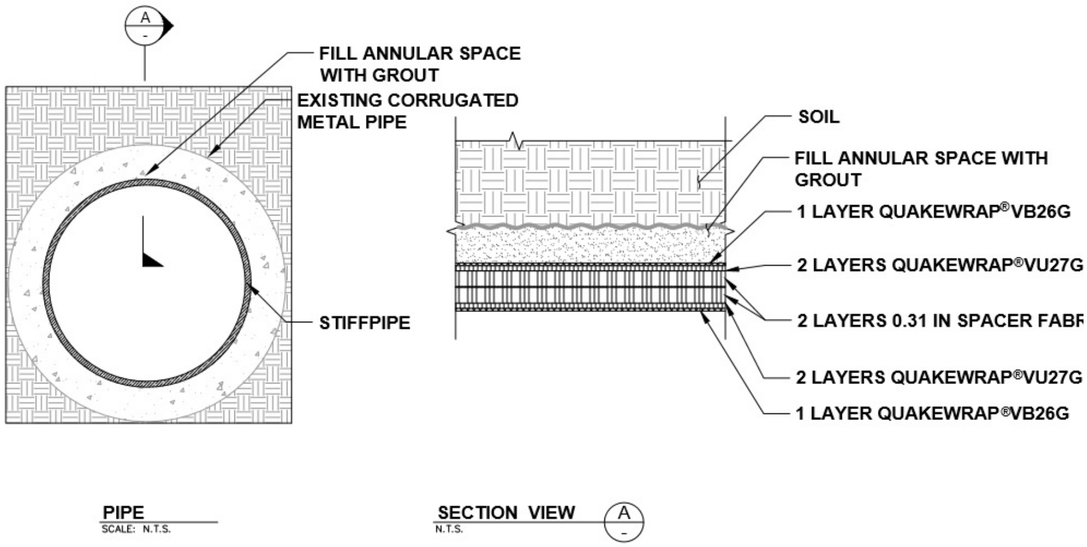


Fig. 3. StifPipe® details

Fig. 4. Construction of StifPipe® at QuakeWrap facilities in Brisbane, Australia

The various layers of fabrics described earlier are wrapped around the mandrel in the proper order. The resin cures in ambient temperature in about 12 hours. If necessary, the mandrel can be heated from inside or outside to accelerate the curing process. The mandrel is partially collapsed, allowing the finished StifPipe® to be removed. The mandrel surface is then cleaned before the next pipe segment is manufactured. The process can be synchronized to follow a 24-hour schedule for construction of each pipe segment. Figure 4 shows the finished 4 segments of StifPipe® prior to shipment to the job site.

6. Field Installation

The finished pipe segments were inspected prior to shipment to the job site. 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 (Fig. 5).

Fig. 5. Transportation of the pipes to the site and placement by 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. 6a). Each segment of StifPipe® weighs only about 1000 pounds (420 kg); 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. 6b). Short pieces of PVC pipe were wedged along the sides and top of the culvert to maintain the annular space between the culvert and StifPipe®.

(a) (b) (c)

Fig. 6. (a) Caster trolleys inside the culvert allowed pushing lightweight StifPipe® segments by hand into the culvert (b); (c) joining of segments with wet layup

Once the proper alignment of all 4 StifPipe® segments was achieved the ends of these pipes were connected together using a wet layup system. As shown in Fig. 6c, 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 effected by coring through the roadway. As shown in Fig. 7, 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. 7). A video detailing this project is available online (https://goo.gl/eCyjhH).

7. 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 (Fig. 5) and during the drilling operation (Fig. 7).

Fig. 7. Coring of the roadway for placement of grout and the finished headwall

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 StifPipe® segments to the site. It is noted that the StifPipe® technology presented here lends itself to continuous manufacturing of the pipe onsite (Ehsani 2015). The Mobile Manufacturing Unit can be set up in front of the culvert and as the pipe is produced, it is pulled into the culvert in a continuous form to create a single 80-ft long liner. This technology referred to as InfinitPipe® will significantly reduce the cost and time required to build the pipes. For example, the MMU can produce pipes at a rate of 1 ft per minute. So the production of 80 feet of pipe for this project could be completed in a few hours.

8. Summary and Conclusions

The repair of the deteriorated CMP culvert in this remote site along a winding road introduced unique challenges. The possibility of bad weather also required the repairs to be performed in a short time frame and not be adversely affected by inclement weather. The use of the innovative StifPipe® resulted in minimal loss of flow capacity, while the light-weight pipe eliminated the need for heavy jacking equipment commonly needed to push the pipes into place. All of these factors resulted in a cost-effective solution that was implemented safely and in 5 days.

As a result of the successful implementation of this project, it is proposed to install a similar sized pipe in a deep gully in a drier, more outback region about 500 miles west of Cairns. Installation is planned for June 2017

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