Designing an Economical FRP System for Pipeline Rehabilitation

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ABSTRACT

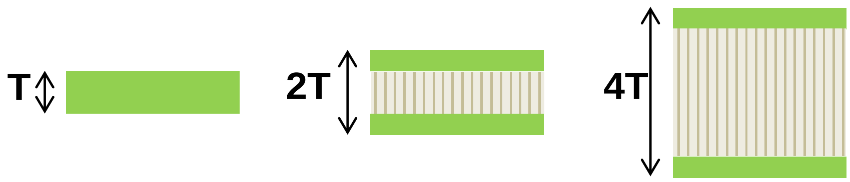
Carbon and glass fiber reinforced polymers (FRP) have been used for infrastructure rehabilitation for more than three decades, and applications in pipeline rehabilitation has gained momentum in recent years. The advantages these systems can provide include high strength, light weight, and ability to be installed on essentially any type of pipe material, size, and geometry. Nevertheless, particularly carbon fiber is an expensive material and if an FRP system is not designed properly the difference in the cost may offset the advantages it provides. This paper will present best design practices with respect to utilizing FRP systems as a more economical alternative for pipeline rehabilitation. Particular emphases will be given to considering the residual strength of the host pipe and using a composite system, which enables achieving high ring stiffness without excessive layers of carbon fiber fabric.

INTRODUCTION

Use of FRP systems for infrastructure rehabilitation has gained more popularity due to the advantages these systems can provide, such as high strength, light weight, ability to be installed on essentially any type of pipe material, size, and geometry, and substantially smaller greenhouse gas (GHG) emissions in comparison with other construction materials (Karbhari and Seible, 2000). Nevertheless, particularly carbon fiber is an expensive material and if an FRP system is not designed properly the difference in the cost may offset the advantages it provides. The common practice for an FRP system design entails accounting for carbon layers only. While carbon fiber is extremely strong in tension (with an ultimate strength well above 130,000 psi); it is not as strong in compression (typically about 50 percent of tensile strength or less). As such, if the external loads on a pipe is significant, then a stand-alone design CFRP system will result in too many layers of carbon with a price greater than other alternatives by multiple folds.

The Sandwich Structure Theory

This obstacle brought about the idea of utilizing the I-beam concept in FRP design by the co-author, Mo Ehsani, back in 2012. Just like a steel I-beam having high stiffness against bending and buckling, a pipe or liner with such structure can have much higher stiffness to buckling due to substantially increased moment of inertia. This is depicted in Figure 1 below.



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

Figure 1. Comparison of stiffness of carbon FRP with carbon FRP applied with a 3D core fabric.

Accordingly, a special type of 3D glass fabric was manufactured and used as an interlaminar layer in a sandwich structure between conventional glass and carbon fiber fabric layers. Sample pipe segments were made with the I-beam fabric (Figure 2) and then tested at the QuakeWrap facility. The results showed significant improvement in ring stiffness with minimal number of carbon fiber layers (Ehsani, 2017).

(a) (b) (c)

Figure 2. Sample of: (a) 3D (I-beam) fabric, (b) the 3D fabric after it has been saturated with resin and allowed to cure, and (c) close-up view of the wall of a StifPipe® made with 3D fabric.

An initial set of tests were conducted on the 1st vintage StifPipe® back in 2015. The test method followed was ASTM D-2412 – “Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading” as an established method to determine the ring stiffness of a flexible pipe. The StifPipe® design used was 2 layers of carbon fiber (TU27C), 2 layers of biaxial glass fiber fabric (VB26G), 1 layer of 3D fabric (Figure 2), and one layer of “chopped mat” which is normally used to increase impermeability, but was utilized for improved resin saturation for this case (Figure 3).

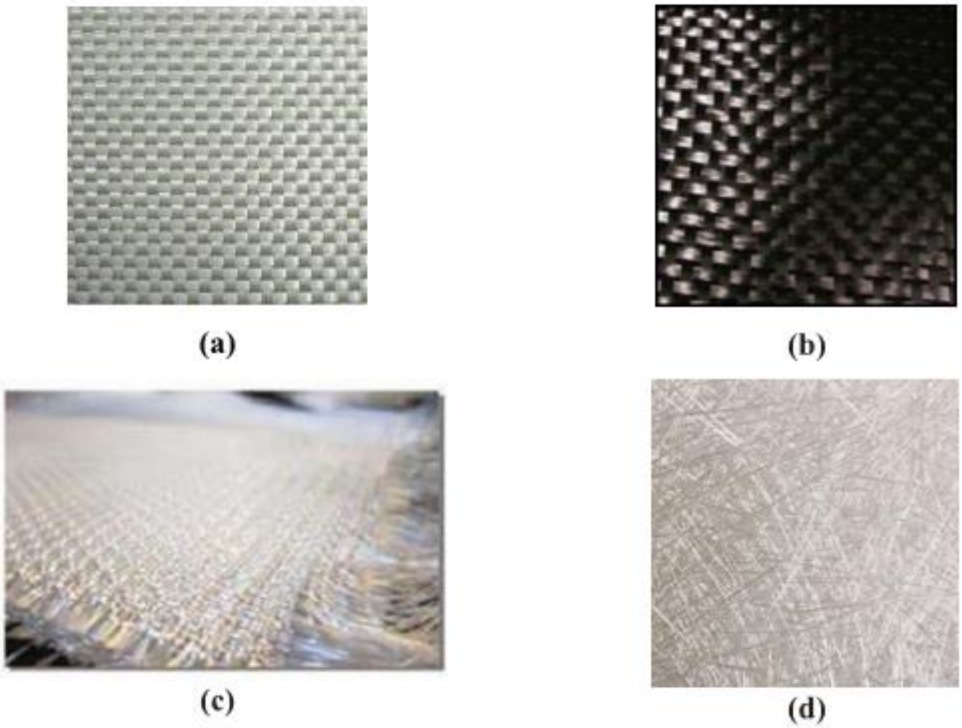


Figure 3. Images of the FRP layers used for the initial parallel plate loading tests applied on the first vintage StifPipe® (a) VB26G Glass Fabric; (b) TU27C Carbon Fabric; (c) 3D Fabric; (d) QuakeWrap® CM 13.5 Chopped Strand Mat

A single StifPipe® segment was manufactured (Figure 4), and then cut into two pieces for testing. The sequence of the FRP fabric layers was as follows:

1. One layer of Chopped mat 2. Two layers of carbon fiber fabric 3. One layer of 3D fabric 4. Two layers of glass fiber fabric.

Figure 4. StifPipe® sample being made on a mandrel by applying resin saturated glass, carbon, and 3D fabric layers.

The loading rate followed the ASTM standard at 0.5 inches of deflection per minute. Load (lb) and deflection (in.) were measured real time. Table 1 below shows a summary of the results in terms of pipe stiffness (PS) calculated using the formula provided in ASTM D2412.

Table 1. Parallel plate load test data from the first vintage StifPipe®

Percentage of outside diameter	3%	5%	8%	10%	15%
Deflection (in)	1.12 in	1.86 in	2.98 in	3.73 in	5.59 in
PS of Sample # 1 (psi)	19.7	19.3	18.4	17.6	N/A
PS of Sample # 2 (psi)	21.5	20.5	19.2	18.5	16.6

Although, the results were impressive for a flexible FRP pipe of 37 inches ID and a total thickness of only 0.5 inches, the level of stiffness was satisfactory for semi-structural rehabilitation only. The proof of concept was achieved, but higher performance was needed to bring StifPipe® to a level of stand-alone pipe in an economical manner. As such, in second tier of experiments a new configuration was used with a custom-engineered polyester 3D (core) fabric (Figure 5). This light weight, high porosity fabric can absorb a lot of resin, thereby increasing the compressive, as well as the flexural strength of the core layer. These two parameters play a major role in increasing the ring stiffness of a pipe.

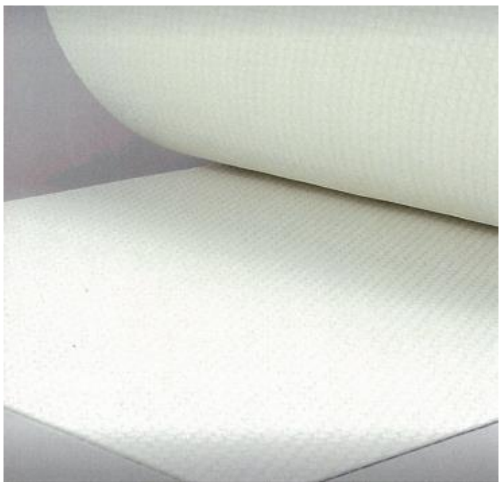


Figure 5. An image of the 3D core fabric used in the new StifPipe®

A new StifPipe® was tested recently with the following configuration:

Four layers of biaxial glass fiber fabric (VB26G)

One layer of 10 mm core mat

Two layers of uniaxial carbon fiber fabric (TU27C)

Implementing the same procedure per ASTM D2412, a load versus deflection from the test results is shown in Figure 6. The test pipe did not fail, and the loading was stopped at 10% deflection. The core mat performed remarkably well in a sandwich structure with glass and carbon fiber layers. The loading capacity exceeded 2,000 lb/ft for the configuration defined above which is only 0.69 in. (17.6 mm) thick (Figure 7).

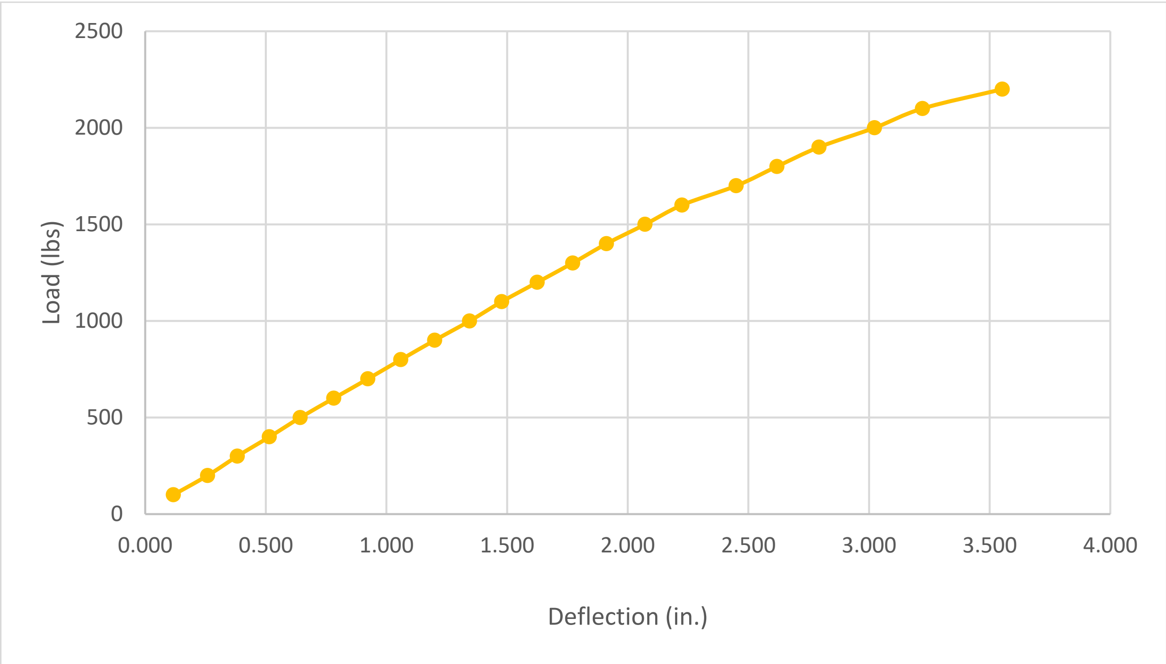


Figure 6. Load vs. deflection plot from the parallel plate loading test on StifPipe® with the custom-engineered 3D core mat.

The more than 2,000 lb/ft of external load the sample StifPipe® was able to withstand is equivalent to more than 30 ft of hydrostatic pressure and is adequate to withstand a soil load most pipes of similar size are subjected to. This light weight and high strength configuration also results in a pipe with minimal GHG during manufacture. In fact, StifPipe® received the 2016 ASCE Innovation Award as the world's first green and sustainable solution for repair and construction of pipelines.

The design, testing, and actual project experience gained to date suggest trying to meet the external loads, particularly, where these loads are high, with carbon fiber fabrics only result in remarkably high layers of carbon fabric, hence high costs of rehabilitation with FRP, rendering this state-of-the-art technology non-competitive on the price in comparison with other methods. The sandwich structure approach geared towards withstanding most of the external loads with a 3D core layer, high in moment of inertia, can save as much as 60% on the cost depending on the size and depth of the host pipe.

Figure 7. A 36-inch StifPipe® at 1,970 lb. of parallel plate load with no apparent sign of a failure.

Case Study 1. 72-inch Prestressed Concrete Pipe Rehabilitation in Amarillo, Texas

A 72-inch water transmission main owned by the Canadian River Municipal Water Authority was recently connected to a steel pipe of same ID, and the owner was concerned about a couple of pipe segments along the 72-inch prestressed concrete pipe (non-cylinder) due to increased stresses and overall age and service conditions. As such, QuakeWrap's construction arm, FRP Construction, was contracted to rehabilitate two 10-ft long segments with an FRP system. QuakeWrap® provided two design options as one conventional CFRP system and the other with StifPipe®. Although the design internal pressure was not low at 100 psi and the soil pressure was not high at 5 ft of cover, the StifPipe® system still saved 30% on the total cost, and owner opted for that option. It should be noted that installing fewer layers of fabric also saves significantly, if not substantially, on the overall labor cost. This was the second StifPipe® installation with the wet layup method (Figure 8), and was completed successfully. The only discrepancy was inadequate saturation of the 3D core fabric along a short segment. This was noticed during the inspection upon installation, and was addressed by additional resin and re-curing that area to obtain full strength of the FRP system with the 3D core layer.

Figure 8. Installation of the FRP with the 3D core sandwich structure (StifPipe®) with the wet layup method[1].

E for the Composite Structure

A design challenge with a somewhat complex sandwich structure is determining the modulus of elasticity in short and long-term. The initial and simple approach for the short-term E was taking the E of each layer and then calculating the combined value based on the moment of inertia of each layer. This can be formulated for a composite with n layers of fabric as follows:

$$E_{c=}\frac{\sum_i^n E_i I_i}{\sum_i^n I_i}$$

This approach, however, is overly simplistic and the test data on StifPipe® samples suggest it substantially underestimates the combined modulus. There are several factors to consider such as the exponential effect of the increased moment of inertia as well as the shear slippage effect among the layers, particularly if the there is not enough adequate resin saturation resulting in reduced adhesion. Development of a more analytical method for calculating E for the StifPipe® is work in progress and more experimental data are needed. Until then, the QuakeWrap® team is using the simple, but overly conservative approach.

SEMI-STRUCTURAL DESIGN

A common practice that may not be necessary and the cost of FRP – or any lining system for that matter – is requiring a fully-structural design when the host pipe has significant residual strength. In fact, most of the underground infrastructure does not require a fully-structural design; hence ignoring host pipe condition and its remaining strength will result in over-design, thereby making

[1] The picture shown is from another project completed in New Jersey (66-inch RCP). Pictures from the 72-inch pipe rehabilitation in Texas were not available at the time of writing this technical paper.

many end users believe that trenchless pipeline rehabilitation is not as economical as it should be.

As such, it is important to keep the concept of semi-structural in mind. Nevertheless, this concept can be complex and might require some assumptions on the strength of the existing conduit where there is not sufficient data.

AWWA M28 classifies water main rehabilitation into four categories. Detailed descriptions of the AWWA water main rehabilitation classification is currently being revised. The classification, as it stands, can be summarized as follows:

1. Class 1: Non-structural rehabilitation for corrosion protection. Examples include thin applied spray applied coatings (cementitious or polymeric).
2. Class II: Semi-structural rehabilitation capable of spanning small holes and gaps. Examples include thicker spray applied linings (cementitious or polymeric).
3. Class III: Semi-structural rehabilitation with inherent ring stiffness and is capable of taking external loads (groundwater pressure) in addition to ability to span small holes and gaps.
4. Class IV: Fully-structural rehabilitation capable of taking all internal (pressure) and external loads on the pipe.

To the best of authors' knowledge, there is no widely accepted such classification on the gravity sewer side. A research project (EPA/WERF INFR1R12, 2012) sponsored by the Water Environment Research Foundation (WERF) as a part of a nationwide EPA program, outlined a simplified version of the AWWA classification for manhole rehabilitation:

Class A: Non-structural rehabilitation for stopping leaks and corrosion protection, if applied to the entire manhole.

Class B: Semi-structural rehabilitation partially relying on the host pipe residual strength.

Class C: Fully-structural rehabilitation as a stand-alone solution capable of taking all the loads exerted on the manhole once installed and cured.

It is important to state the purpose of a rehabilitation project, know the host pipe condition, and evaluate the rehabilitation solutions with the classifications listed above.

Case study 2 – TATA Power, Bahira Penstock Rehabilitation, India

The QuakeWrap® team is currently working on a design solution for a 36-inc (914 mm) diameter penstock that is suffering from significant wall loss due to internal corrosion. The original steel conduit was from 25 to 27 mm thick and had lost up to 30 percent of its wall thickness based on an ultrasonic inspection conducted more than a decade ago. The owner is looking into an economical rehabilitation solution without being have to shut the system down as there is no redundancy. A fully structural design would require an FRP solution that is essentially equivalent to 27 mm of steel, and could require more than 10 layers of carbon fiber resulting in a high cost. With the semi-structural rehabilitation approach, QuakeWrap® was able to meet a safety factor of 2.0 by using only four layers of carbon fiber and one layer of biaxial glass fiber fabric layers reducing the rehabilitation cost by more than 50 percent in comparison with the fully-structural design option. The lining will be performed externally without interrupting the service, thereby avoiding any costs associated with a hydroelectric power plant shutdown.

CONCLUSIONS

FRP systems are continuing to provide a viable alternative for pipeline rehabilitation, and the use of FRP systems for particularly large diameter pressurized piping systems is growing. Nevertheless, better design practices and education of the end users are needed to get the best out of these high-tech materials in achieving cost competitiveness. With such design practices it is fair to assume that the use of these materials will also grow in the gravity flow pipe systems (mainly storm and sanitary sewers) given the advantages they provide such as high strength, minimal thickness, smooth surface (often increasing hydraulic capacity upon rehabilitation) and ability to accommodate any geometry. With the right design practices that utilize the expensive component, carbon fiber, for internal pressures and tensile stresses only, as well as understanding that a fully-structural rehabilitation is a too conservative approach for the majority of the pipelines out there will enable engineers and owners to enjoy the great benefits of these materials to maximum extent.

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