Composite Reinforcement of Wrinkle Bends Subjected to High Strain-Low Cycle Bending Loads

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Abstract

Composite materials are commonly used in the reinforcement of hoop-oriented defects such as corrosion, dents, seam-weld anomalies, and gouges within pipelines. Additionally, they can be designed to reinforce features susceptible to cracking when subjected to bending and tension loading, including girth welds and wrinkle bends. Of particular interest, given historical failure patterns, is when wrinkle bends are subjected to high strain-low cycle fatigue loads.

This paper presents results and findings of a study that involved full-scale testing of wrinkle bends. The test program encompassed three distinct tests on 26-inch x 0.281-inch, Grade X52 pipes, all of which had wrinkles removed from service. The test program comprised testing an unreinforced wrinkle bend sample, as well as two additional samples that were reinforced with custom-designed E-glass-epoxy and carbon-epoxy composite technologies with axial-dominant fiber architectures.

In the case of the unreinforced wrinkle sample, the maximum recorded axial strains in the wrinkle feature were +/- 1%, in which the sample failed after 107 bending cycles. The two composite reinforced samples utilizing the E-glass-epoxy and carbon-epoxy technologies failed after 1,774 and 863 bending cycles, respectively. These results demonstrate that both systems were able to increase the life of the unreinforced wrinkle sample by as much as 16 times.

From an operational standpoint, these findings imply that the service life of existing wrinkle bends could be substantially prolonged, potentially by decades, assuming that such bends are subjected to loads of similar magnitude 5-10 times per year, as examined in this study. This research offers valuable insights into the transformative role of composite materials in enhancing the longevity and durability of wrinkle bends in pipelines.

Introduction and Background

A study was conducted that involved full-scale testing of composite reinforced wrinkle bend samples subjected to internal pressure and cyclic bending loads. The testing program consisted of three wrinkle samples: one unreinforced sample serving as a control, and two samples reinforced by OmegaWrap's composite materials. Of the two reinforced samples, one was reinforced with the axial-dominant OmegaWrap EG system, which utilizes an E-glass fabric, and the second test sample was reinforced with the axial-dominant OmegaWrap C system that utilizes a carbon fabric. Both technologies employee a two-part epoxy resin matrix. The wrinkle bend samples were extracted from a pipeline sample provided by Boardwalk Pipelines. The pipe was a 26-inch OD x 0.281- inch WT, API 5L Grade X52 material.

The purpose of the program was to determine the benefits that composite reinforcements would have on the fatigue lives of wrinkle bends subjected to fully reversible bending load cycles (i.e., subjecting the wrinkles to tension and then compression). Previous studies have shown that the use of composite materials can mitigate threats associated with wrinkle bends due to the additional axial stiffness provided by the reinforcements. The outcomes from this study provide additional data and information on how much reduction occurs in axial strain at the wrinkle and axial displacement across the wrinkle, and the increase in cycles to failure associated with the composite reinforcements. Table 1 provides a summary of the pipe sample sizes, composite material selection, and wrinkle information described by the wrinkle height (H), wrinkle length (L), and H/L ratio. All wrinkles were retrieved from the same pipe sample and had similar H/L ratios. Figure 1, Figure 2, and Figure 3

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show the wrinkle geometries. For the reinforced samples pre and post composite installations photographs are shown for reference.

Table 1. Wrinkle samples summary

Sample	Pipe Dimensions	Pipe Material	Wrinkle Height [H] (inch)	Wrinkle Length [L] (inch)	Wrinkle H/L Ratio
Unreinforced	26-inch OD x 0.281-inch WT	API 5L Grade X52	0.813	3.625	0.224
Reinforced with E-glass			0.813	3.625	0.224
Reinforced with Carbon			0.750	3.688	0.203

Figure 1. Unreinforced wrinkle with instrumentation

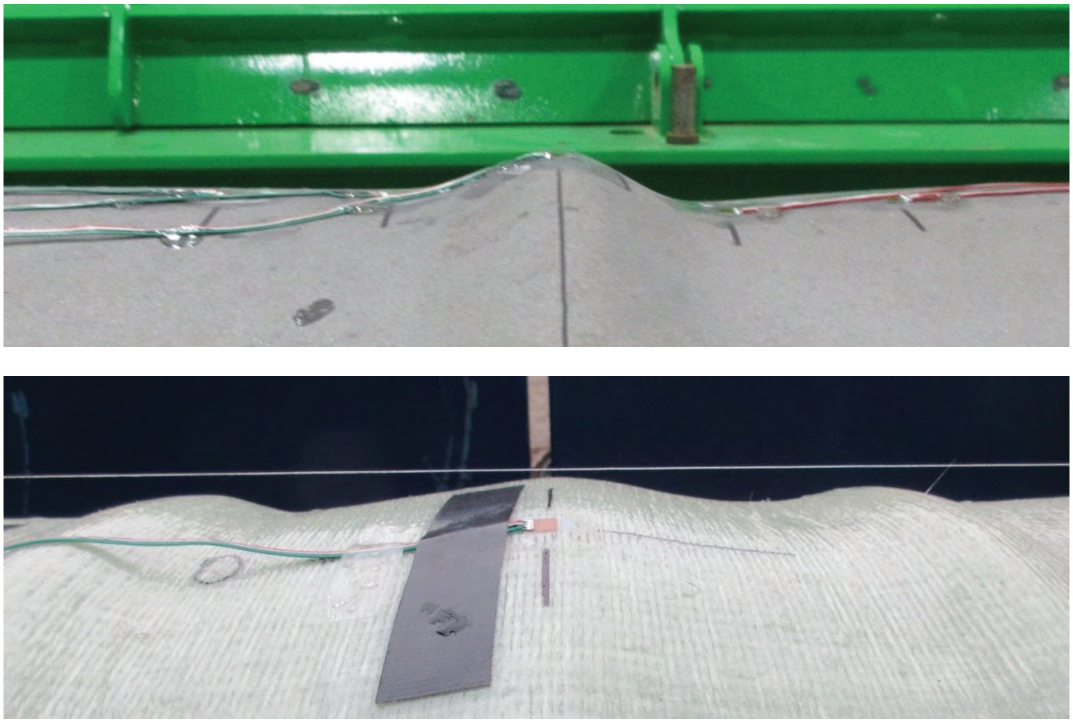

Figure 2. Wrinkle pre (top) and post (bottom) repair with E-glass

Figure 3. Wrinkle pre (top) and post (bottom) repair with carbon fiber

Testing Methods

The program consisted of full-scale testing of wrinkles subjected to internal pressure and bending, as well as sub-scale testing of composite coupons. Sub-scale testing was used to quantify material properties of the selected composite fabrics to ensure strength and elastic modulus were present, and to provide technical data to determine the required thickness for the repairs. Full-scale testing permitted a complete assessment of the composite reinforcing systems, where the metrics used to evaluate performance were number of cycles to failure and strain reduction in the reinforced wrinkle.

The sections that follow provide details on the composite installation work and methods used to conduct the full-scale testing effort.

Composite Installation

A combination of hoop-dominated and axial-dominated fibers were used in reinforcing the wrinkle bends. The conventional hoop-dominated systems can be used to reinforce the majority of pipeline features and defects; however, the use of axial-dominated composite repair fabrics are required whenever the maximum principal stresses are oriented in the axial direction or circumferentially oriented defects require reinforcement. Examples where axially dominated composites are required include the reinforcement of girth welds and wrinkle bends, the latter of which is the subject of this study.

Figure 4 and Figure 5 are photographs of the E-glass and carbon systems installed on the respective wrinkle bend samples. The repair lengths were approximately 37 inches. The same number of layers (12) were installed on both the E-glass and carbon test samples and included the following fabric lay-up. The total thickness of the E-glass repair was approximately 0.535 inches and the thickness for the carbon system was 0.336 inches.

Layers #1 & #2:	**Axial-dominated layers**
Layer #3:	Hoop-dominated layer
Layers #4 & 5:	**Axial-dominated layers**
Layer #6:	Hoop-dominated layer
Layers #7 & #8:	**Axial-dominated layers**
Layer #9:	Hoop-dominated layer
Layers #10 & #11:	**Axial-dominated layers**
Layer #12:	Hoop-dominated layer

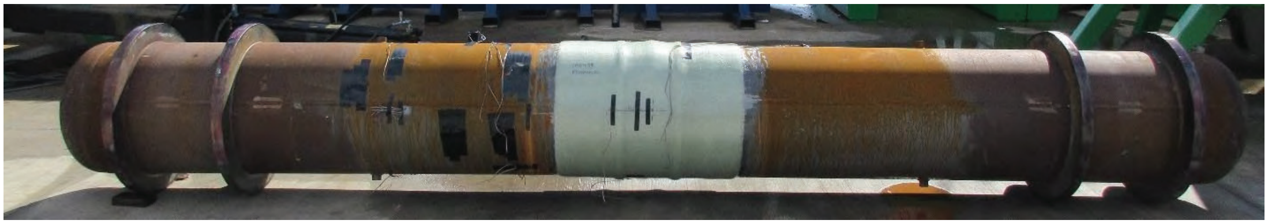

Figure 4. Wrinkle sample reinforced with E-glass composite wrap

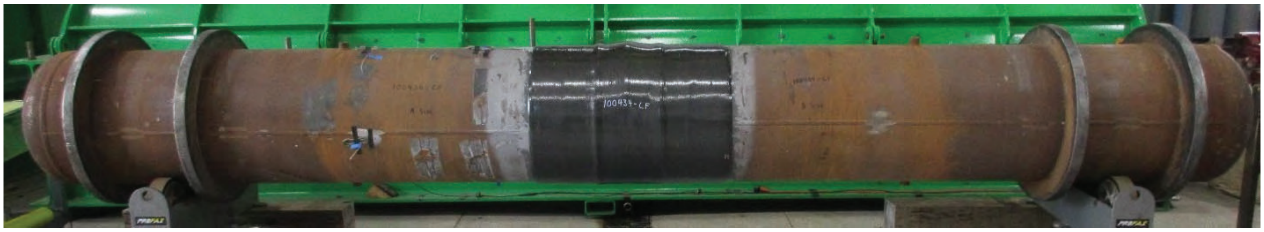

Figure 5. Wrinkle sample reinforced with carbon fiber composite wrap

Full-scale Test Setup

The full-scale testing program involved fabricating pipe samples to be tested in the bending load frame. Fabrication consisted of welding the wrinkle sample between two thick-wall pup pieces that would interface with the test fixtures. The bending load frame allows for a fully reversible bending load application by utilizing opposing hydraulic two cylinders that generate a moment couple up to 1 million ft-lbs, as shown in Figure 6.

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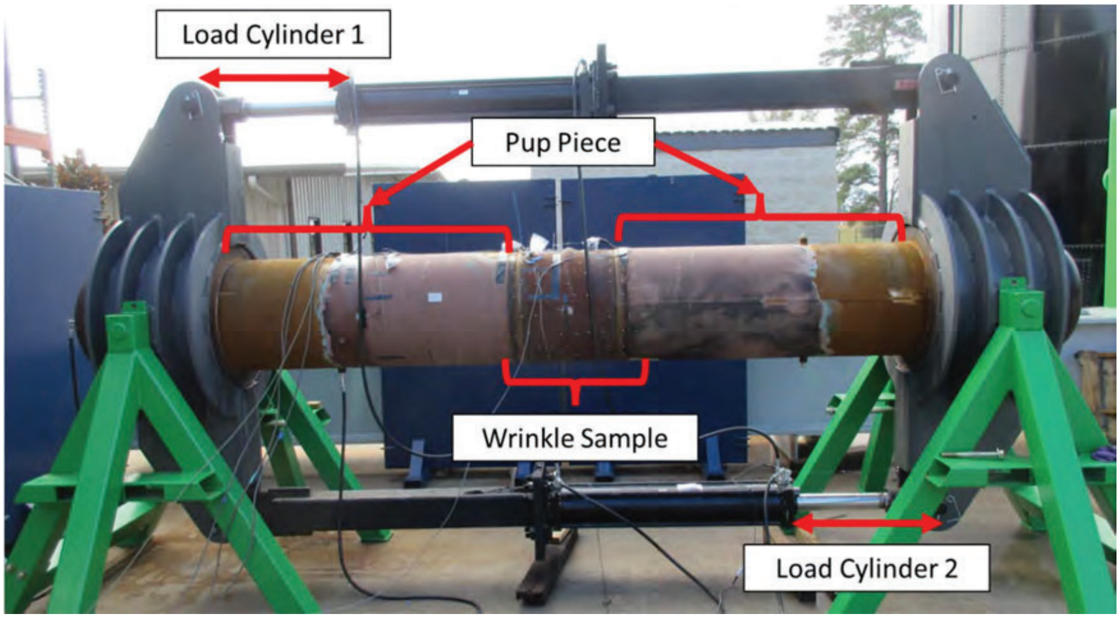

Figure 6. Wrinkle sample setup in bending load frame (unreinforced sample)

All three pipe samples (one unreinforced and two reinforced) followed a similar test setup. Biaxial strain gages were placed at critical locations including the wrinkle peak/crest and valley/trough to measure the hoop and axial strains. Figure 7 is a schematic showing the strain gage locations installed on the test sample, while Figure 8 is a photograph showing strain gages installed near and on the wrinkle of the unreinforced test sample.

A string potentiometer was placed across the wrinkle axial length to measure the axial displacement of the wrinkle during loading. Figure 9 is a schematic showing the displacement transducer (i.e., string potentiometer) location on the test samples, while Figure 10 is a photograph showing the string potentiometer on the carbon reinforced test sample. Pressure transducers were installed to measure the internal pressure of the sample as well as the internal pressure of the hydraulic cylinders.

From a loading standpoint, the unreinforced sample used a displacement-driven configuration (i.e., bending moment applied to achieve a specified displacement at the wrinkle); whereas the reinforced samples were subjected to a force-driven configuration. The reason for this approach is two-fold. First, prior to testing it was determined that a certain level of strain must be generated in the wrinkle of sufficient magnitude (e.g., 1 percent) to achieve a failure in approximately 150 cycles. From previous testing conducted by the authors, high strain / low cycle conditions have produced short fatigue lives in both actual pipeline service and in test lab conditions.

Secondly, once a wrinkle is reinforced, it is not possible to accurately measure displacement across the wrinkle. In its reinforced condition, the wrinkle will never experience the same magnitude of displacement as the unreinforced wrinkle because of the increased stiffness provided by the composite materials. Hence, reinforced wrinkle bend testing should always be loaded using a force-driven configuration. In this study, the bending moment range used to achieve the "target" 1% axial strain was applied to the reinforced wrinkle bend test samples.

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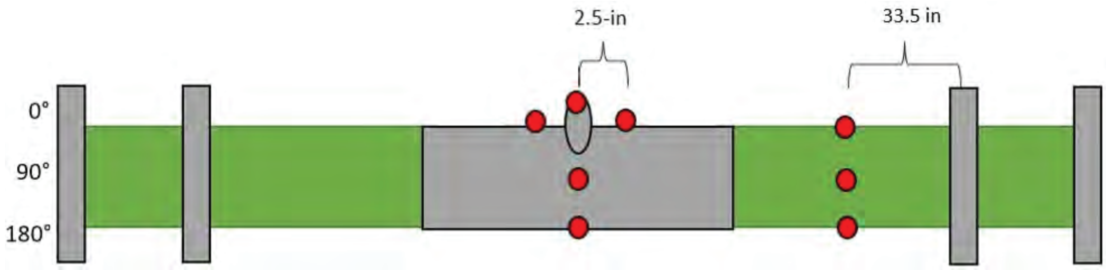

Figure 7. Reinforced sample gage locations

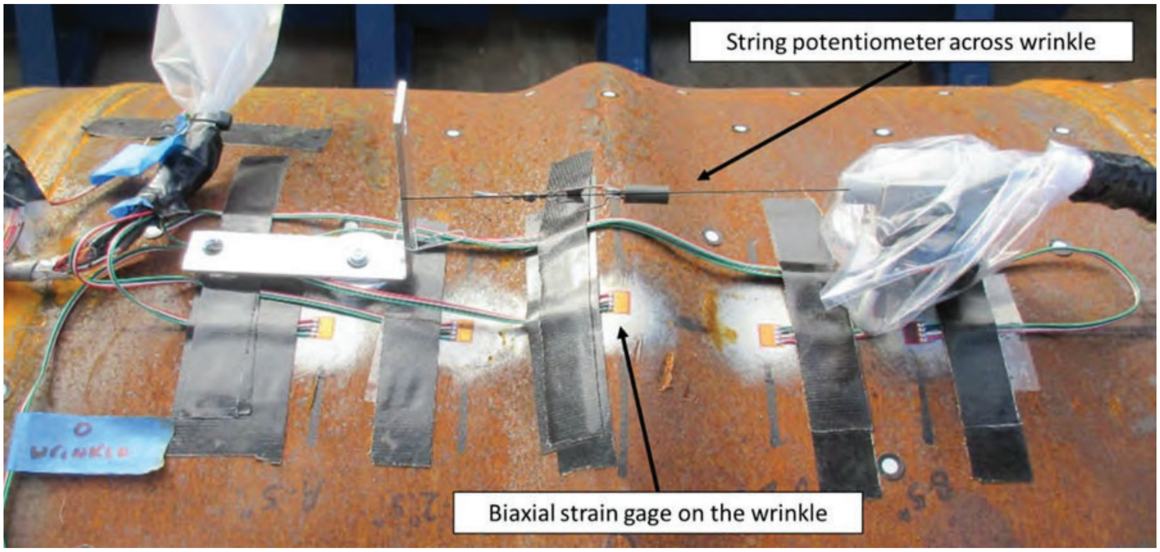

Figure 8. Biaxial strain gages and string potentiometer on wrinkle sample
(Unreinforced sample shown)

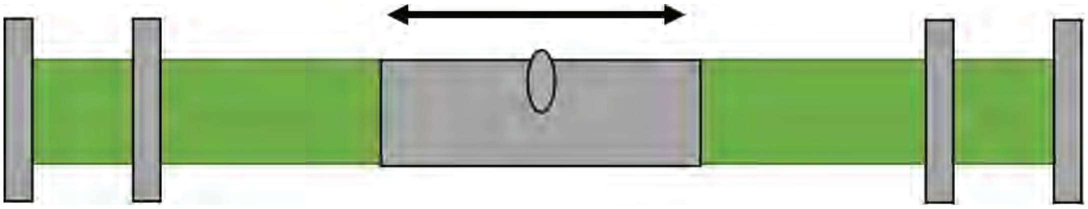

Figure 9. Displacement transducer locations

Figure 10. String potentiometer installed on a reinforced wrinkle
(Carbon fiber reinforced sample shown)

The test samples were placed in the bending frame as shown in Figure 11 (unreinforced sample). The samples were pressurized to an internal pressure corresponding to 72% SMYS (810 psig), where the pressure was held between 750-850-psig for the duration of the test. A bending moment was applied to the sample until a failure occurred, which is characterized by loss of internal pressure due to a leak.

For the unreinforced sample, which was tested first, the bend cycles were controlled using axial displacement across the wrinkle values between +/- 0.1-inch (i.e., displacement controlled). During this particular test the applied bending moment was extracted and subsequently applied to the reinforced sample, thus generating a “load controlled” testing configuration. For the reinforced samples, the bend cycles were controlled using the measured bending moment range.

Figure 11. Unreinforced sample in bending frame

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Test Results

The following sections provide details on the sub-scale and full-scale testing. The material property measurements obtained from sub-scale testing were important to determine the geometry for the wrinkle bend reinforcements. Of particular interest was the elastic modulus values in the hoop and axial directions.

Sub-scale Test Results

Table 2 below provides a summary of the tensile test results associated with both the carbon and E-glass epoxy systems including average tensile strength and modulus of elasticity in the hoop and axial directions for the axial-dominant fabrics. The strength and elastic modulus values for the hoop-dominant layers, installed every third layer (i.e., 3, 6, 9, and 12), are approximately the same as those for the axial-dominant layers, but oriented 90 degrees relative to the values presented in the table below.

As observed in the tabulated data, the elastic modulus for the carbon system is approximately three times that of the E-glass system. Although not tabulated, the average strain-to-failure for the carbon system was approximately 1.0%, whereas the E-glass system was approximately 2.0%. The strain-to-failure values are important in scenarios where composite repairs can experience large levels of strain, such as the reinforcement of wrinkle bends.

If strains in the composite reach strain-to-failure values during loading, microcracking in the reinforcement will develop and the repair will no longer be able to provide the level of reinforcement it originally provided. Understanding strain-to-failure values is an important design consideration and as will be demonstrated in this study, for the same thickness level the E-glass material has an advantage over the carbon technology in the reinforcement of wrinkle bends subjected to high strain / low cycle bending loads.[1]

Table 2. Summary of tensile test results for the axial-dominant fabrics

System	Axial Direction		Hoop Direction	
	Average Tensile Strength (Standard Deviation)	Average Modulus (Standard Deviation)	Average Tensile Strength (Standard Deviation)	Average Modulus (Standard Deviation)
Carbon epoxy	147,400 psi (9,700 psi)	14,900,000 psi (880,000 psi)	20,200 psi (1,400 psi)	2,450,000 psi (470,000 psi)
E-glass epoxy	82,600 psi (3,800 psi)	4,933,000 psi (224,000 psi)	10,100 psi (3,800 psi)	1,307,500 psi (275,000 psi)

Full-scale Test Results

As stated previously, full-scale testing involved applying bending loads to the test samples until an axially oriented crack developed in the wrinkle bend. Figure 12 shows a typical applied bending moment cyclic load scenario where the pipe sample experienced an average bending moment range of 840 ft-kips. This figure shows a few representative bending cycles for ease of interpreting the data.

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[1] It is important to note that there are conditions where carbon-epoxy technologies are the only logical choice among competing composite systems. Examples include the reinforcement of crack-like features and planar defects, where the larger elastic modulus of the carbon technology ensures that stresses at the crack tip are minimized to minimize crack propagation.

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All samples were subjected to the same loading mechanism following the same cyclic regime. Figure 13 shows the response of the axial strain at the wrinkle peak due to the cyclic bending load.

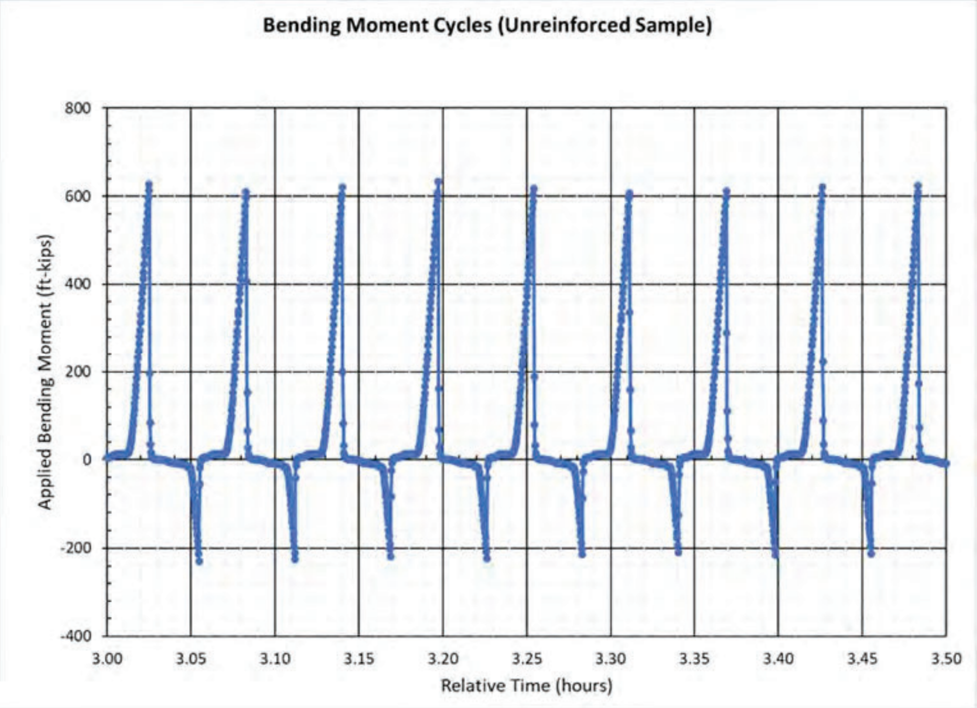

Figure 12. Applied bending moment cyclic regime

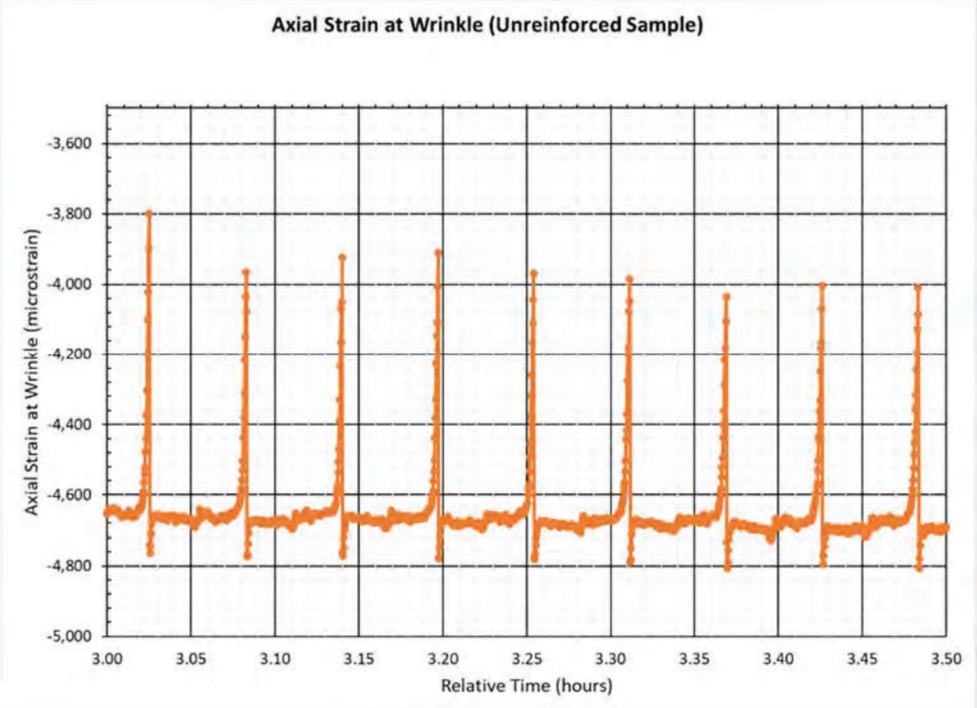

Figure 13. Axial strain at the wrinkle peak due to cyclic bending

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Testing was concluded after failure of the wrinkle, which is characterized by a drop in internal pressure due to leaking associated with a circumferential crack that developed in the peak of the wrinkle. The unreinforced sample leaked after 107 bend cycles while the E-glass reinforced sample leaked after 1,774 (an increase of 16.6 times) and the carbon reinforced sample leaked after 863 cycles (an increase of 8.1 times). Provided in Figure 14 is a photograph showing the crack that developed in the peak of the wrinkle of the unreinforced test sample.

Table 3 provides a summary of the results for all three samples including the bending moment range, maximum axial strain at the wrinkle, and maximum axial displacement across the wrinkle. All data shown in the tables are strain range peak-to-peak values (i.e., the difference between the maximum and minimum values during one cycle).

Table 3. Summary of axial strain range results

Cycle #	Unreinforced			Carbon Reinforcement			E-glass Reinforcement		
	Bending Moment (ft-kips)	Axial Strain Range at Wrinkle (microstrain)	Axial Displacement (inches)	Bending Moment (ft-kips)	Axial Strain Range at Wrinkle (microstrain)	Axial Displacement (inches)	Bending Moment (ft-kips)	Axial Strain Range at Wrinkle (microstrain)	Axial Displacement (inches)
1	984	9,153	0.212	801	3,412	0.080	820	4,279	0.087
10	877	7,844	0.203	823	2,254	0.083	825	4,252	0.090
25	846	7,784	0.202	822	2,156	0.085	820	N/A (1)	0.087
50	834	7,655	0.194	823	2,156	0.081	836	N/A	0.087
100	812	6,759	0.203	823	1,982	0.079	838	N/A	0.088
200				825	2,738	0.080	830	N/A	0.091
500				822	2,153	0.086	832	N/A	0.093
750				826	3,671	0.082			

NOTE: (1) Valid strain gage measurements were no longer available during these cycles, likely due to disbonding of the strain gage beneath the composite repair.

Figure 14. Photograph showing leak that developed in peak of the wrinkle bend

Conclusions

The primary conclusion from this study is that composite materials can effectively reinforce wrinkle bends subjected to extreme bending loads. One of the important observations in this study was that the E-glass increased the fatigue life of the reinforced wrinkle more than the carbon-reinforced test sample. Although there has been a general trend over the past five years in the pipeline industry where carbon-epoxy technologies have been used to reinforce an increasing number of pipeline defects, historical research has shown that E-glass technologies can be used for most all repairs, with the notable exception being axially oriented cracks and planar defects where hoop stiffness (i.e., elastic modulus) is critical.

The strain to failure for most E-glass technologies (2%) is typically two times greater than the strain to failure for carbon systems (i.e., 1% or less). Higher modulus carbon systems (e.g., 30 to 40 Msi), not used in the pipeline industry, have strain-to-failure values on the order of 0.4%. Because strain in the unreinforced wrinkle approached 1%, it is possible that fractures in the fibers of the carbon system fractured during the application of cyclic bending loads. For applications such as the reinforcement of wrinkle bends, for the same number of layers E-glass technologies can be expected to provide as good or better fatigue lives, which is an important economic consideration as carbon material by weight is more expensive than E-glass.

It should be noted that had more layers of the carbon technology been installed on the wrinkle bend sample, the performance of this repair would have increased; however, considering the carbon technology is more expensive this hardly seems like a prudent move. The work documented in this report provides a framework for quantitively evaluating wrinkles with or without composite reinforcements based on maximum local strains in the wrinkles and the number of cycles to failure subject to high strain / low cycle loading conditions.

Test results showed that for wrinkles with similar H/L ratios, the presence of composite reinforcements significantly improve the fatigue lives of wrinkle subjected to bending loads that would be experienced in geohazard loading conditions. Although both the carbon and E-glass systems can be used to reinforce wrinkles, for the same equivalent thickness the E-glass system was found to be the better performing technology.

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