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STATE-OF-THE ART ASSESSMENT OF COMPOSITE REPAIR TECHNOLOGIES

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ABSTRACT

For more than 30 years composite repair technologies have been used to reinforce high pressure gas and liquid pipeline transmission systems around the world. The backbone of this research has been full-scale testing, aimed at evaluating the reinforcement of anomalies including, corrosion, dents, vintage girth welds, and wrinkle bends. Also included have been the assessment of reinforced pipe geometries including welded branch connections, elbows, and tees. Organizations sponsoring these research efforts have included the Pipeline Research Council International, regulatory agencies, pipeline operators, and composite repair manufacturers. Many of these efforts have involved Joint Industry Programs and to date more than 20 different industry-sponsored programs and independent research efforts have been conducted involving more than 2,000 full-scale destructive tests.

The lessons learned by the research completed for the pipeline industry can be applied to applications for piping applications. The aim of this paper is to provide for industry with an updated perspective on research associated with composite repair technologies. Because of the continuous advance in both composite technology and research programs to evaluate their effectiveness, it is essential that updated information be provided to industry to minimize the likelihood for conducting research efforts that have already been addressed. To provide readers with useful information, the author will include multiple case studies that include the reinforcement of corrosion, girth weld, and planar crack-like defects.

Keywords: Composites, non-metallic, repair, reinforcement, corrosion, cracks, and pipelines.

1. INTRODUCTION

Over the past 30 years composite technologies have changed the landscape in how high pressure transmission pipelines are repaired and U.S. pipeline regulations have supported their innovative usage [1]. Prior to their introduction the only repair options for pipeline operators were welded steel sleeves or replacement via welding in full-encirclement cylinders. Today, composite materials can repair practically any geometry or defect.

The use of composite materials will only increase considering the age of our pipeline infrastructure, our ability to detect and locate defects using advanced inspection technologies like in-line inspection, and the increased demand on our pipeline system by a public that requires (and demands) more energy. Our country cannot function without transmission pipelines, especially natural gas pipelines that fuel over 43% of our electric power grid . Future requirements associated with powering artificial intelligence data centers will only increase demands on our electrical grid. The bottom line is composite materials are essential to safely maintain our transmission pipeline systems.

While ASME PCC-2 [2] has done a good job providing guidance for the reinforcement of corrosion features, in its current state it does not provide guidance for the reinforcement a myriad of other features including mechanical damage, dents, pipe bends and elbows, tees, branch connections, long seam weld planar defects (especially those associated with LF-ERW (low frequency electric resistance weld) longitudinal seams), wrinkle bends, girth welds, and cracks. Fortunately, the composite repair community that includes manufacturers, pipeline operators, regulators, and researchers have continued to advance the state-of-the-art and funded more than $35 million (USD) since 2005 in research to validate the use of composite reinforcing technologies involving more than 25 Joint Industry Project full-scale testing research programs.

The material in this paper is heavily weighted towards pipeline industry applications, including the testing configurations and case studies. However, pressure vessels and piping face similar issues as pipelines when considering the damage mechanisms associated with corrosion and cracks, both of which are explored in this paper. For additional information, interested readers are encouraged to review some of the technical articles listed in the REFERENCE section of this paper.

Provided in each discussion associated with reinforcement of corrosion and crack-like features is a basic description of the defect and its associated threat level, supporting data based on prior testing work, and proposed design guidance.

2. REINFORCEMENT OF CORROSION FEATURES

The majority of composite repairs involve the reinforcement of corrosion features. Their application is widespread across plants, refineries, and pipelines. The standard to which composite repairs are designed in North America is ASME PCC-2. The design equations in ASME PCC-2 have been validated beyond anything the original authors could have ever envisioned. In addition to extensive testing used to quantify the long-term design strength of the composite materials using 1,000-hour and 10,000-hour tests, more than 350 burst and pressure cycle tests have been conducted to validate Equation 12, one of the three main composite reinforcement design equations in the current version of ASME PCC-2.

Although ASME PCC-2 provides three different options for design, the most common option used for repairing transmission pipelines is based on PCC-2 Equation 12 that calculates the minimum required composite thickness, t_s. This equation is as follows in Equation (1):

$$t_{min} = \left(\frac{PD}{2} - t_s S\right)\left(\frac{1}{f \cdot S_{lt}}\right) \tag{1}$$

Where:

P	Design pressure
D	Pipe diameter
S	Pipe yield strength
t_s	Corroded pipe wall thickness (remaining)
f	Service factor from ASME PCC-2 Table 401-3.4.5.1
S_{lt}	Long-term strength

A review of Equation 12 yields the following observations.

- Included as the contribution of the remaining pipe wall to the overall strength of the reinforced pipe is the product of t_s and S. The strength of this remaining ligament reduces the required composite thickness when compared to what would be required were the composite required to carry the entire load.
- Not included in this equation is corrosion length. For shorter corrosion features some experts have argued that too much composite material is installed using PCC-2 Equation 12 because corrosion length is not included as a design variable, resulting in an overdesign condition.
- Equation 12 includes long-term composite strength, as well as a service factor used to establish the design strength of the composite material. The service factor is the reciprocal of the safety factor. A safety factor of 2.0 is associated with a 1,000-hour test period, while a safety factor of 1.5 is associated with a 10,000-hour test period. The longer test period (i.e., 14 months for 10,000 hours versus 42 days for 1,000 hours) compensates composite manufacture designs with a reduced wall thickness.

In the early 1990s when composite materials were first being used and tested in reinforcing corrosion features, the primary focus was on burst tests. By the early 2000s it was clear that additional data was required to evaluate hoop strain in the reinforced regions of the pipe, as well as the need to establish service life based on pressure cycle testing. Another body of work completed circa 2020 was the PRCI MATR-3-4 study [3] that involved the burial of 12-inch pipe samples with corrosion features having depth of 40%, 60%, and 75% of the pipe's nominal wall thickness. Thirteen different repair systems were tested with testing periods up to 10 years. The general conclusion was that all tested system performed well for the 40% corrosion features, but that some of the systems did not perform as well at the more severe 75% corrosion levels.

The subsequent sections address the following topics:

1. Description of the feature and the threat it poses to pipeline integrity.
2. Supporting data and references based on previous research and testing.
3. Proposed stress (or strain) limits that dictates the geometry of the composite reinforcement.

2.1. Feature Description and Associated Threat Level

The reinforcement of corrosion is the most common use of composite repair systems and represents the "base use case" for which all repair systems must be validated. The traditional burst test involves pressurizing a reinforced pipe sample to failure. Within ASME PCC-2 there is a required "spool survival test" that utilizes a relatively thin repair that must reach a failure pressure based on the actual yield strength of the pipe. This test is an excellent qualification test that also validates the performance of the load transfer (filler) material installed in the machined corrosion feature.

It is rare for composite repair systems to not pass the spool survival test, although it is still a good qualification test. However, the more aggressive performance test is the cyclic pressure test that is not required by ASME PCC-2. The most common test involves the reinforcement of a 75% deep corrosion feature (8 inches long by 6 inches wide) in a 12.75-inch x 0.375-inch, Grade X42 pipe sample cycled from 890 psig to 1,780 psig (ΔP = 36% SMYS). The systems that have been tested using cyclic pressure by the author used Equation 12 with the 1,000 hour long-term design strength [3].

Although a pass-fail criterion does not currently exist when it comes to composite repairs tested in fatigue, the number of cycles to failure reached by a particular system can be used to establish the design fatigue life for the system. This is achieved using a fatigue safety factor, such as 5.0. Consider the example below based on results for Armor Plate® Pipe Wrap that have been widely published [4].

- Number of cycles to failure: 259,537 cycles @ ΔP = 36% SMYS (890 to 1,780 psig)
- Design life based on experimental fatigue data = 51,907 cycles (259,537 cycles / 5.0)
- Assume a pipeline in operation experiences 250 cycles per year @ ΔP = 36% SMYS
- The resulting service life: 207 years based on 51,907 design cycles / 250 cycles per year

Gas transmission pipelines typically experience minimal pressure cycling, so concerns related to fatigue are minimal and any calculation of service life will likely be hundreds of years. However, liquid pipeline operators must be cognizant of their operating conditions and consider the number of pressure cycles experienced annually. In the previous example, if the pipeline experienced 1,500 cycles per year (rather than the 250 used in the calculation), the resulting service life is 35 years.

The author has tested systems that failed after as few as 20,000 pressure cycles, so operators are encouraged to review any data provided by a manufacturer. The inability of a composite repair system failing to reach at least 150,000 pressure cycles is typically associated with a composite having an inadequate stiffness, defined as the product of elastic modulus and thickness. Another cause of poor performance is a load transfer material that is not stiff enough. The failure mechanism in the reinforced steel is due to a high strain, low cycle condition, similar to how a paperclip fails when subjected to extreme bending conditions.

2.2. Supporting Data

In the open literature there is a significant body of data available on the performance of composite materials used to reinforce corrosion features. ASME PCC-2 provides excellent guidance that can be used with confidence. What is not addressed explicitly in ASME PCC-2 is the reinforcement of corrosion features subject to cyclic pressure conditions. Fortunately, this is an area that has been addressed extensively via full-scale testing. Complete data sets are available for approximately 10 different composite repair systems; results are presented for the Armor Plate® Pipe Wrap system in part because they were widely disseminated at conferences and workshop circa 2010. Provided below is supporting data that provides insights on the design of composite reinforcement for reinforcing corrosion features.

- The "backbone" of full-scale testing when it comes to reinforcing corrosion features is the burst test. Early work in the early 1990s focused on increasing the burst pressure capacity of reinforced test samples having simulated corrosion features. However, by the 2000s it was clear that a deeper understanding on load transfer was required, and strain gages were used to provide the necessary insights. Provided in Figure 1 is a plot showing hoop strain as a function of internal pressure for a 12.75-inch x 0.375-inch, Grade X42 pipe with a 75% deep corrosion feature (8 inches long and 6 inches wide). Strain is plotted for two gages installed in the corrosion region beneath the filler material of the repair, one gage installed on top of the repair, and one gage installed on the base pipe away from the repair. At the 72% SMYS design pressure (1,780 psig) the measured hoop strain in the corroded region was 0.32%. This measured value is well below the average hoop strain measured among the following 13 companies that participated in the PRCI MATR-3-4 "buried pipe" study.
- In his Ph.D. work, Alexander [5] determined that at design pressure conditions the strain in the reinforced region of the corrosion should be limited to 0.4%. This was based on research conducted on the long-term performance of E-glass and carbon fiber technologies. As an example, at design conditions the Armor Plate® Pipe Wrap system had a maximum hoop strain in the corroded region that was less than this value. This value also proved to be important when considering fatigue performance as plotted in Figure 2, where the maximum measured hoop strain was 0.32% and the strain range never exceeded 0.15%. The design for this particular repair was based on ASME PCC-2 Equation 12.
- Not all composite repair system performed equally in pressure cycle testing, even though they meet the minimum requirements of ASME PCC-2. This is illustrated in the data provided in Figure 3. Cyclic pressures from 36% to 72% SMYS (890 to 1,780 psig) were applied to 75% corrosion features in 12.75-inch x 0.375-inch, Grade X42 pipe samples. Over the past 20 years this test has been performed on more than 20 different composite repair systems, provided in this list are results for 10 systems. As noted, not all performed well, although each of these systems met the minimum requirements of ASME PCC-2, including passing the spool survival test. As observed, two systems did not even reach 50,000 cycles before a crack developed in the reinforced corrosion region of the pipe (beneath the repair). The Armor Plate® Pipe Wrap system reached almost 260,000 cycles and serves as an exemplar data set for how a well-designed system can perform. The strain measurements taken on the burst and pressure cycle samples provide excellent reference points for other systems. Many of today's current commercially available technologies have similar results with fatigue lives exceeding 150,000 applied pressure cycles.

2.3. Proposed Design Guidance

Unlike the reinforcement of other features addressed in this document where ASME PCC-2 does not provide prescriptive guidance, using Equation 12 from ASME PCC-2 will provide a well-designed repair system for reinforcing corrosion considering both static and cyclic pressure loading. For gas pipelines that experience minimal pressure cycling there are no major concerns on fatigue life. However, installation on liquid pipelines requires additional consideration and full-scale testing is strongly recommended. As presented in the previous example, a fatigue safety factor of 5.0 is recommended and the pipeline operator-provided pressure history data can be used to determine the service life for the particular pipeline.

In terms of limits, at design pressure conditions (72% SMYS) for 75% deep reinforced corrosion features, a maximum hoop strain of 0.4% in the reinforced (corroded) steel is recommended. In terms of pressure cycling with ΔP = 36% SMYS a hoop strain range of 0.2% is recommended, ensuring that the maximum hoop strain does not exceed 0.4%. Of course, in testing strain gages are required to make strain measurements.

3. REINFORCEMENT OF CRACK-LIKE FEATURES

The reinforcement of axial cracks represents a significant technology advance in the history of composite repairs. When composite repair technologies started to gain acceptance in the pipeline community in the late 1990s the majority of repairs were made using E-glass materials; however, with advances in the introduction, validation, and adoption of carbon fiber materials the game changed. In the transmission pipeline community, the first repair companies who used carbon fiber technologies included Citadel (now CSNRI) and TEAM (now Furmanite).

Chevron circa 2014 [6,7] conducted an extensive study that evaluated the performance of composite repair systems at 250°F and included 10,000-hr creep testing. TEAM participated in this study with their carbon repair technology and PipeWrap (which became Milliken and is now CSNRI's Atlas technology) also participated. The first use of carbon fiber technology on a transmission pipeline in the U.S. was based on a testing program funded by Boardwalk [8] that involved the evaluation of the Atlas technology reinforcing planar defects in 16-inch pipe having vintage LF-ERW seam pipe. This study in particular opened the door for the future use of composite repair technologies in reinforcing planar defects and crack-like features. A comprehensive study was also funded by ExxonMobil from 2017-2019 [9].

The next major body of work to evaluate the reinforcement of planar defects and axial cracks was initiated by Sergio Limon and Chris Alexander who organized a Joint Industry Program that evaluated three carbon epoxy technologies that included systems from CSNRI, TEAM, and Omega Wrap [10]. Funding for this JIP was provided by three manufacturers: CSNRI, OmegaWrap, TEAM, as well as eight pipeline companies: Boardwalk, Enbridge, Kinder Morgan, Northern Natural, SoCalGas, PG&E, TC Energy, and Williams. The program evaluated the performance of these systems in reinforcing two vintage pipe materials: 1940-era 12-inch pipe with LF-ERW seams and 1950-era 30-inch pipe manufactured by A.O. Smith. In this research study manufacturers and researchers were able to evaluate various design configurations and calculation methods, all of which integrated fracture mechanics calculations in their designs.

The sections that follow provide information on the threat level associated with axial cracks, supporting experimental data, and proposed design guidance.

3.1. Feature Description and Associated Threat Level

With advances in in-line inspection (ILI) technologies, especially in relation to detecting and sizing crack features, pipeline operators are required to evaluate a larger number of planar defects and axial cracks than ever before in the history of pipeline operation. With the increasing number of cracks associated with continued operation of an aging asset class, this trend is only expected to continue. For this reason, it is imperative that well-proven repair technologies by readily available for use.

Axial cracking poses a threat to transmission pipelines for multiple reasons. First, cracks can be difficult to detect and size, including limitations with hand-held in-the-ditch inspection technologies. Without accurate feature sizing it is difficult to perform integrity assessment calculations used to estimate burst pressures and fatigue lives. Secondly, for most transmission pipeline systems there is an absence of accurate material properties, especially fracture mechanics properties that are required to perform fracture mechanics calculations. Similar to issues related to crack sizing, it is impossible to accurately predict failure pressures absent material properties. Finally, failures due to cracks in transmission pipelines are often catastrophic. Failures in liquid pipelines can result in significant environmental damage as the leaking product goes into the surrounding soil and adjacent stream and lakes. Because of the energy present in high pressure large diameter gas pipelines, failures in gas transmission pipelines are often catastrophic in terms of the debris and only made worse if an ignition source is present.

So, with all of the above commentary, the pipeline industry welcomes repair technologies for reinforcing cracks. The key to reinforcing cracks is reducing stress in the crack (specifically, the crack tip) and minimizing localized stresses that occur with increased and / or cyclic pressures. Because of their elevated stiffness levels, carbon epoxy technologies are able to "take on" loading from the pressurized pipe sooner than their E-glass counterparts. Although E-glass materials are excellent for reinforcing most pipeline features that include corrosion, dents, wrinkle bends, fittings, and perhaps even girth welds, at the current time only carbon-fiber technologies should be used to reinforce cracks. Additionally, only carbon-fiber technologies with adequate strain-to-failure should be used. High modulus carbon technologies have superb stiffness values due to their elevated Young's modulus (e.g., on the order 40 Msi), but their low strain-to-failure levels (e.g., on the order of 0.30%) prevent them from being useful in most pipeline applications.

3.2. Supporting Data

When considering the reinforcement of cracks, composite material works in conjunction with the pipe to reduce stresses in the crack. The material properties of the pipe dictate the magnitude of reinforcement that must be provided by the composite. For example, a pipe steel that behaves in a non-ductile manner, as often observed with planar defects in LF-ERW seams, must be treated differently than a pipe steel that fails in a ductile manner. The required prior knowledge on the fracture toughness properties of the steel is necessary to design an optimized repair solution. In the absence of such data, composite designers are wise to assume lower bound material properties.

As stated previously, a JIP was led by Limon and Alexander [10] that evaluated three different carbon-epoxy technologies. All systems performed well and are suitable for application on actual pipeline systems. Two of the companies performed their own calculations; however, Vendor B worked with ADV Integrity and employed the design approach developed by Alexander, which is included in this document. Provided in Table 1 are results from the JIP that include results for select unreinforced and reinforced test samples.

The unreinforced samples all failed in less than 10,000 pressure cycles, while the reinforced samples all survived 25,000 pressure cycles and were then burst tested. What is equally impressive is that even after burst testing the crack growth in the reinforced samples was less than 7.8% for the test samples included in this table. These results are important as the applied pressure ranges during cycling were from 100 psig up to 72% SMYS. From the work completed by Kiefner et al [11] at a ΔP = 65% SMYS, an "Aggressive" condition that represents liquid pipelines is 98 cycles per year and a "Light" condition representing a typical natural gas pipeline is 14 cycles per year. Therefore, assuming a fatigue safety factor of 5.0 the 25,000 experimental cycles represent 5,000 design cycles. So, prior to burst testing the composite samples were subjected cyclic pressure loading simulating 357 years for a typical natural gas pipeline and 51 years for a typical aggressively cycled liquid pipeline. As noted in Table 1 all failures for the reinforced samples failed in the base pipe and successfully retarded crack growth in the crack-like defects that in the unreinforced samples failed after an average of 6,165 pressure cycles were applied. Post-test macrographs are provided in Fig. 4 and Fig. 5.

3.3. Proposed Design Guidance

The reinforcement of axially oriented cracks has been a subject of interest for many years. Until the introduction of carbon-epoxy technologies there was minimal incentive for the pipeline industry to explore this application. Numerous studies have been conducted to evaluate the use of composite technologies for reinforcing cracks, including the first "high-profile" study funded by Boardwalk Pipelines [8] that involved the reinforcement of a 16-inch ethylene pipeline. CSNRI's Atlas technology was tested in this program and even though a thick repair was tested (i.e., 1.0-inch thickness), the full-scale test results were positive and convinced PHMSA the pipeline could be repaired. After that study numerous other programs focused on rack reinforcement were funded by composite repair companies in an effort to advance their state-of-the-art capabilities.

More recently, a Joint Industry Program completed in late 2021 involving nine pipeline operators and three composite repair companies was conducted. The study evaluated the reinforcement of cracks in 1940-era 12-inch LF-ERW pipe and 1950-era 30-inch A.O. Smith pipe material. Provided below is the methodology developed for this study. These calculations require the use of a fracture mechanics software, such as the MAT-8 software, or access to full-scale burst pressure results. However, the basic principles outlined below provide guidance on how to design a composite repair system for reinforcing cracks. The concept is to calculate a composite thickness to achieve a certain stress "reduction" level in a reinforced pipe to ensure a stable response of the crack-like feature. Listed below are the steps involved in this process.

1. Identify the pipe geometry and material properties. If available, obtain the actual material properties and material toughness. In the absence of actual material data, conservative assumptions are required.

2. Obtain crack geometry, including depth and length.

3. Using a fracture mechanics calculation method, estimate the burst pressure for the unreinforced pipe considering the crack geometry (i.e., MAT-8, API 579, BS7910, etc.). Alternatively, use full-scale burst testing to determine the burst pressure (i.e., empirically derived burst pressure). The latter will produce the most accurate solution.

4. Using either the empirically determined or calculated burst pressure, use Barlow's equation to calculate the nominal failure stress (i.e., hoop stress at failure) at the burst pressure using the nominal pipe wall thickness.

5. Calculate a design stress by imposing a safety factor on the nominal failure stress (i.e., design stress = nominal failure stress / safety factor). For the empirically derived value a safety factor of 2.0 is recommended. Additionally, if fatigue life is a consideration the calculated design stress can be used to estimate fatigue life. <u>If a longer fatigue life is required, increase the safety factor.</u> Provided below in Equation (2) is the API X' fatigue curve [12] where Δσ is the stress range in psi.

$$N = 2{,}000{,}000\left(\frac{\Delta\sigma}{11{,}400}\right)^{-3.74} \quad (2)$$

6. Calculate the composite thickness using Equation (3), which is derived from the Barlow-based composite reinforced pipe stress based on strain compatibility (Equation (4)).

$$t_c = t_s\left(\frac{E_s}{E_c}\right)\left(\frac{PR}{\sigma t_s} - 1\right) \quad (3)$$

$$\sigma_s = \frac{PR}{t_s(1 + \frac{E_c t_c}{E_s t_s})} \quad (4)$$

Provided below are copies of the EXCEL calculator used to estimate the composite thickness assuming a crack depth of 50%, an elastic modulus of 12.3 Msi, and the failure pressures for the unreinforced 12-inch and 30-inch NPS based on burst tests. No internal pressure during installation was assumed. The resulting composite thicknesses for the 12-inch and 30-inch pipes were 0.387 inches and 0.612 inches, respectively. Provided in Fig. 6 is the calculator that determined these thicknesses using the above equations.

4. CONCLUSIONS

Composite materials will continue to play a critical role in the integrity management programs of all major pipeline companies, especially when one considers the age of our pipeline system and our ability to detect and locate features and defects using advanced ILI technologies. Composite reinforcements are also widely used in power plants, chemical plants, and refineries. The requirements for permanent repairs associated with buried high-pressure transmission pipeline applications have driven the extensive body of research. The ability for using composite reinforcements in a temporary capacity in plant applications reduces some of the demands for permanent repairs in these environments.

One of the knowledge gaps that exists among plant applications is the performance of composite reinforcements at elevated temperature conditions. A large body of work was completed for Chevron that involved the testing of three different composite repair technologies up to 120°C (250°F) that included 10,000-hour creep testing and immersion of the repairs on full-scale 12-inch pipe samples in a brine water solution [6,7].

Today's composite repair companies and pipeline operators are to be commended for their support of research and Joint Industry Programs in collaborating together to advance the state-of-the-art. This level of collaboration is a model for what regulators want to see in substantiating technologies and ensuring they have been validated for long-term service.

REFERENCES

[1] Pipeline Safety: Gas and Hazardous Liquid Pipeline Repair, Federal Register, Vol. 64, No. 239, Tuesday, December 14, 1999, Rules and Regulations, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733; Amdt. 192-88; 195-68 (Effective date: January 13, 2000).

[2] American Society of Mechanical Engineers, ASME Post Construction SC-Repair & Testing, PCC-2, Repair Standard, Article 4.1, Non-metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications, New York, New York, 2015 edition.

[3] Alexander, C., "Advanced Techniques for Establishing Long-Term Performance of Composite Repair Systems", Proceedings of IPC 2014 (Paper No. IPC2014-33405), 10th International Pipeline Conference, September 29 - October 3, 2014, Calgary, Alberta, Canada.

[4] Alexander, C., and Bedoya, J.J., "Developing an Engineering Based Integrity Management Program for Piping, Pipelines, and Plant Equipment", Proceedings of the ASME 2014 Pressure Vessels & Piping Conference (Paper No. PVP2014-28256), July 20-24, 2014, Anaheim, California.

[5] Alexander, C.R., (December 2007), "Development of a Composite Repair System for Reinforcing Offshore Risers," Ph.D. Dissertation, Texas A&M University, College Station, Texas.

[6] Alexander, C., Sheets, C., Harrell, P., Rettew, R., Baranov, D., "Experimental Study of Elevated Temperature Composite Repair Materials to Guide Integrity Decisions", IPC 2016, 11th International Pipeline Conference, IPC2016-64211, September 26-30, 2016 Calgary, Alberta, Canada.

[7] Alexander, C., Sheets, C., Rettew, R., Azenova, T., "Full-Scale Elevated Temperature Testing of Composite Repairs in Bending and Compression", 11th International Pipeline Conference, IPC2016-64213, September 26-30, 2016 Calgary, Alberta, Canada.

[8] Alexander, C., Rizk, T., Wang, H., Clayton, R., Scrivner, R., "Reinforcement of Planar Defects in Low-Frequency ERW Long Seams Using Composite Reinforcing Materials", Proceedings of IPC 2016 (Paper No. IPC2016-64082), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.

[9] Futch, D., Sheets, C., Bagnoli, K., Cabrera, R., and Koetting, S., *REX Deep Dive - Composite Repair of Crack-Like Features*, PRCI REX Conference, Paper No. PRCI-REX2021-036, February 2021.

[10] Limon, S., Alexander, C., Holloman, R., and Futch, D., Fatigue Growth Behavior of Cracks in Pipelines Reinforced by Carbon Composite Wraps, 2022 Pipeline Pigging & Integrity Management (PPIM) Conference, February 2022, Houston, Texas.

[11] Kiefner, J., Estimating Fatigue Life for Pipeline Integrity Management, Paper No. IPC04-0167, 2004 International Pipeline Conference, September 2004, Calgary, Alberta, Canada.

[12] API Recommended Practice 2A-WSD, Planning, Designing, and Constructing Fixed Offshore, Platforms—Working Stress Design, 22nd edition, Nov. 2014.

[13] Alexander, C., Kania, R., Zhou, J., Vyvial, B., Iyer, A., "Reinforcing Large Diameter Elbows Using Composite Materials Subjected to Extreme Bending and Internal Pressure Loading", Proceedings of IPC 2016 (Paper No. IPC2016-64311), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.

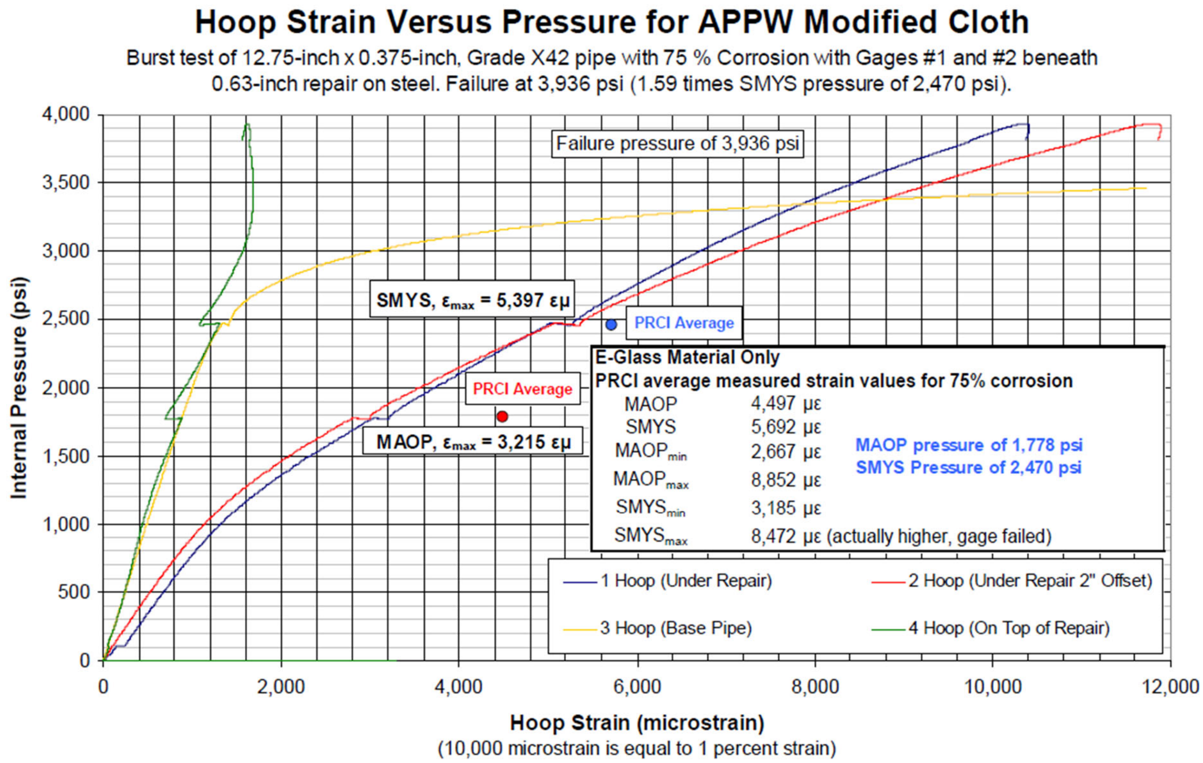

FIGURE 1: HOOP STRAIN AS A FUNCTION OF INTERNAL PRESSURE FOR A REINFORCED 75% CORROSION FEATURE

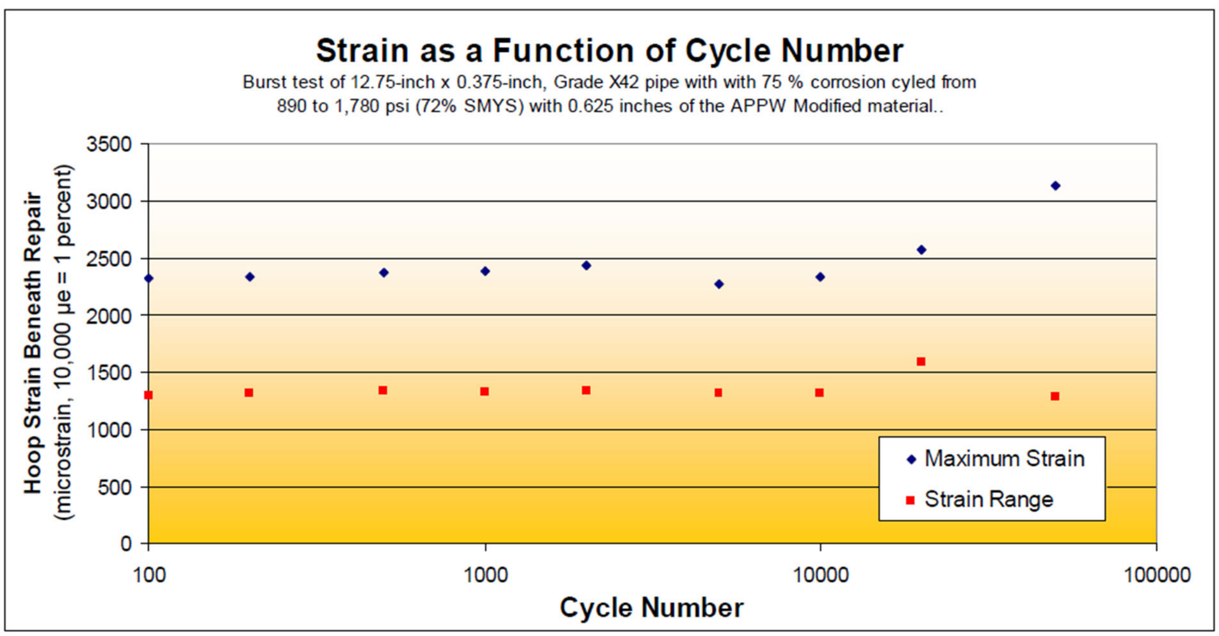

FIGURE 2: MAXIMUM HOOP STRAIN AND RANGE MEASURED IN THE REINFORCED 75% DEEP CORROSION FEATURE

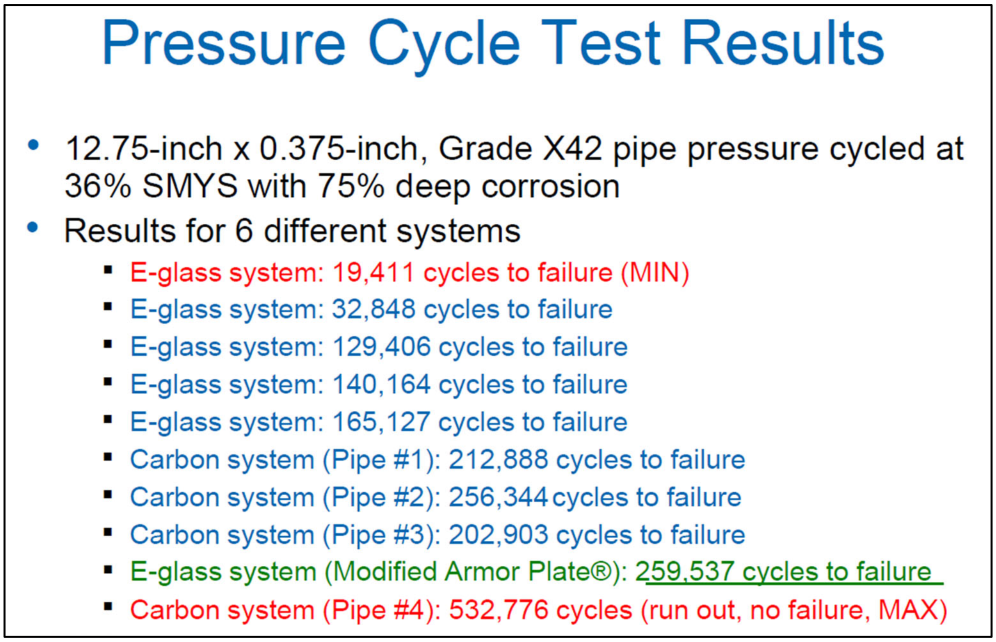

FIGURE 3: COMPARISON OF FATIGUE DATA FOR DIFFERENT COMPOSITE REPAIR SYSTEMS

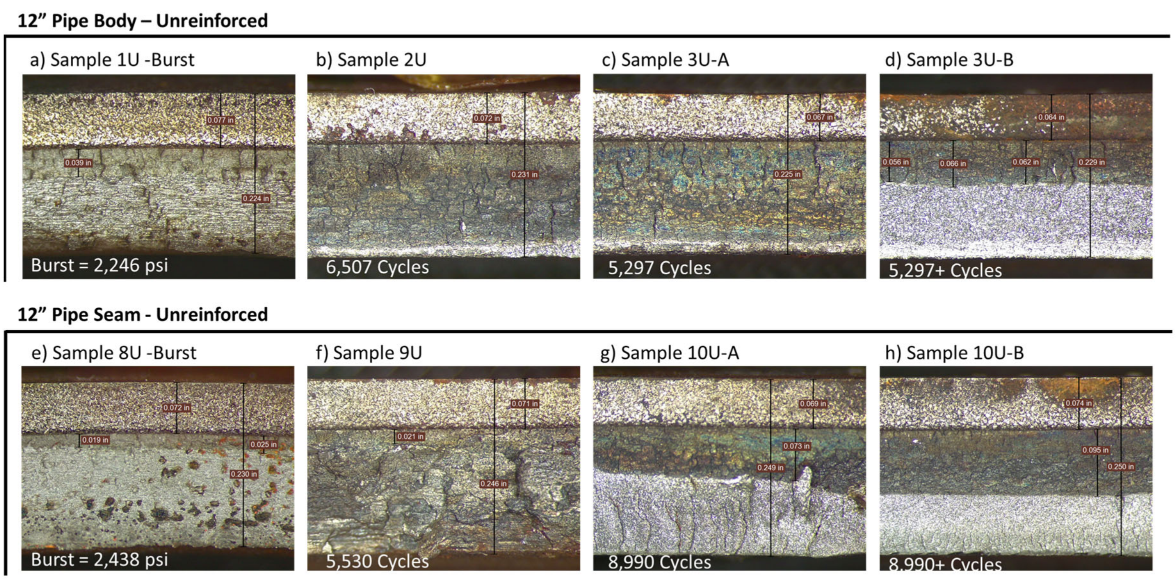

FIGURE 4: FRACTURE SURFACES OF UNREINFORCED PIPE SAMPLES (SAMPLES 1U AND 8U WERE BURST TESTS)

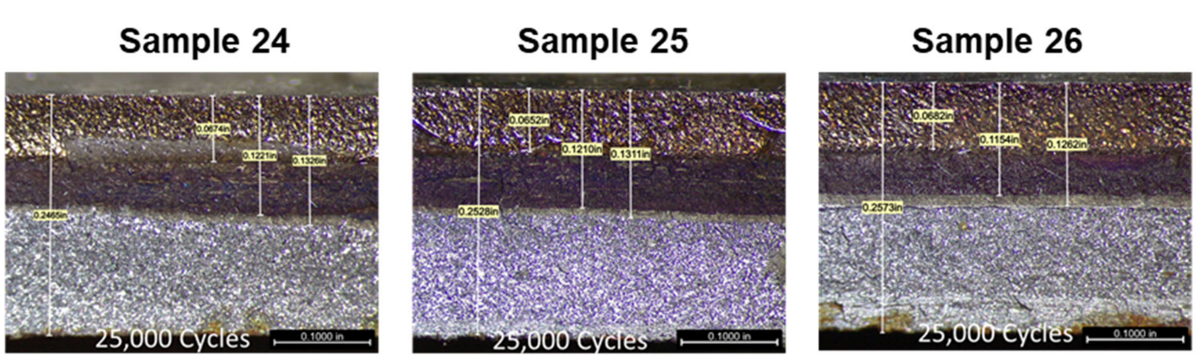

FIGURE 5: FRACTURE SURFACES OF SELECT REINFORCED PIPE SAMPLES (SAMPLES 24-26, VENDOR B)

12-inch Pipe Sample

D	12.75	inches
R	6.375	inches
t_s	0.25	inches
Crack depth (%)	50%	(Sample 8U)
t_{s_rem}	0.125	inches
E_s	29,000,000	psi
E_c	12,300,000	psi
σ_y	46,000	psi
Design (72% SMYS): P	1,299	psig
P_{burst}	2,246	psig
MAT-8 P_{burst}	1,538	psig
f	2.00	Safety factor
σ_{burst}	57,273	psi
σ_s	28,637	psi
t_c (P_{live} = 0)	**0.387**	**inches**
Fatigue Calculations		
$N(\sigma_{burst})$	4,777	cycles
$N(\sigma)$	63,822	cycles

30-inch Pipe Sample

D	30	inches
R	15	inches
t_s	0.375	inches
Crack depth (%)	50%	(Sample 8U)
t_{s_rem}	0.188	inches
E_s	29,000,000	psi
E_c	12,300,000	psi
σ_y	52,000	psi
Design (72% SMYS): P	936	psig
P_{burst}	1,570	psig
MAT-8 P_{burst}	1,251	psig
f	2.00	Safety factor
σ_{burst}	62,800	psi
σ_s	31,400	psi
t_c (P_{live} = 0)	**0.612**	**inches**
Fatigue Calculations		
$N(\sigma_{burst})$	3,384	cycles
$N(\sigma)$	45,221	cycles

FIGURE 6: FRACTURE MECHANICS CALCULATOR USED TO DETERMINE COMPOSITE THICKNESSES

TABLE 1: SELECT FATIGUE RESULTS FOR UNREINFORCED AND REINFORCED SAMPLES

Pipe Size (inches)	Sample Number	Pressure Range (psig)	Initial Crack Depth (% w.t.)	Repair Thickness (inches)	Applied Fatigue Cycles	Final Crack Depth Growth (% w.t.)	Failure Mode and Location
Unreinforced Pipe Samples							
12	2U	100 to 1,300	31.2	N/A	6,507	68.8	Fatigue failure in crack
	3U	100 to 1,300	29.8	N/A	5,297	70.2	Fatigue failure in crack
30	5U	100 to 940	34.8	N/A	4,273	65.2	Fatigue failure in crack
	6U	100 to 940	34.9	N/A	4,871	65.1	Fatigue failure in crack
	7U	100 to 940	33.2	N/A	7,685	66.7	Fatigue failure in crack
12	9U	100 to 1,300	28.9	N/A	5,530	71.1	Fatigue failure in crack
	10U	100 to 1,300	27.7	N/A	8,990	72.3	Fatigue failure in crack
Reinforced Pipe Samples (Vendor B)							
30	21R	100 to 940	40.7	0.786	25,000	7.8	Burst at 157% SMYS in Unreinforced Seam
	22R	100 to 940	39.2	0.786	25,000	5.1	Burst at 145% SMYS in Unreinforced Base
	23R	100 to 940	42.6	0.786	25,000	6.1	Burst at 156% SMYS in Unreinforced Base
12	24R	100 to 1,300	49.5	0.623	25,000	4.3	Burst at 148% SMYS in Unreinforced Base Pipe
	25R	100 to 1,300	47.9	0.623	25,000	4.0	Burst 163% SMYS in Unreinforced Base Pipe
	26R	100 to 1,300	44.9	0.623	25,000	4.2	Burst at 158% SMYS in Unreinforced Base Pipe