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Guidelines for Using Composite Materials to Repair High Pressure Transmission

Prepared for

Dominion Energy

Project No. DOM-17-018

WHEN TECHNOLOGY WORKS, TREMENDOUS THINGS ARE POSSIBLE.

May 2018

Guidelines for Using Composite Materials to Repair High Pressure Transmission Pipelines

Prepared for

Dominion Energy

Salt Lake City, Utah

May 2018

STATE OF TEXAS
CHRISTOPHER R. ALEXANDER
108453
LICENSED
PROFESSIONAL ENGINEER

Prepared by:

Dr. Chris Alexander, P.E.
chris.alexander@advintegrity.com

Project No. DOM-17-018

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Tuesday, May 1, 2018

Mr. Joe Fox
Dominion Energy
1140 200 S
Salt Lake City, UT 84104
E-mail: joe.fox@dominionenergy.com
Mobile: (801) 580-0268

SUBJECT: Composite Repair Guideline Document

Joe,

Enclosed you will find the *Composite Repair Guideline Document* that has been prepared for Dominion Energy. Included in this document you will find work associated with my research on composite repair materials over the past 10 years, although my first research work on composite repair technologies started in 1994 in evaluating the Clock Spring technology. The research has focused on high pressure gas and liquid transmission pipelines; as such, the anomalies we've evaluated are those typically associated with transmission pipelines, as opposed to those associated with gathering and distribution pipelines.

The pipeline industry continues to "push the envelope" in terms of composite repair usage. Today, we are repairing features like planar flaws in seam welds and stress corrosion cracking that would never been considering, or permitted, 20 years ago. The composite repair manufacturers have continued to advance that state-of-the-art based on needs specified by pipeline operators. I expect we will continue to see advances in composite repair technologies with improvements in inspection and monitoring technologies. The key is to balance risk and ensure that the repair technologies we install can be trusted to perform at the levels required by both operators and regulators.

Thank you for this opportunity. Please let me know if you have any questions.

Regards,

Chris Alexander

Dr. Chris Alexander, PE, President
chris.alexander@advintegrity.com

28213 Meadow Forest
Magnolia, Texas 77355
281.450.6642
ADVINTEGRITY.COM

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EXECUTIVE SUMMARY

ADV Integrity, Inc. (ADV) was contracted by Dominion Energy (Dominion) to develop a guideline document for using composite materials to repair and reinforce high pressure transmission pipelines. Composite materials are widely-accepted as a viable means for repairing transmission pipelines by both operators and regulators. Since 2008 the Pipeline Research Council International, Inc. (PRCI) has actively supported research programs associated with composite repair materials, resulting in seven different investigations. Countless other independent research efforts sponsored by both composite manufacturers and pipeline operators have also been performed. The insights gained from these efforts have contributed significantly to industry's understanding on composite repair technologies and the development of this document.

This guideline document includes a section for Dominion that discusses how to properly use composite repair systems to ensure the long-term integrity of their pipeline systems. This section provides instructions for properly using composite materials, including information on assessing pipeline defects, designing a composite repair system using industry accepted-standards such as ASME PCC-2, and proper installation methods and techniques. The old adage, *You get what you inspect, not what you expect*, has been the driver in developing this section of the guideline document. <u>Having a set of specific requirements that can be enforced through documentation and inspection is the key for Dominion in properly using composite repair systems.</u>

Dominion's interest in developing a composite repair guideline document is well-founded. As an industry, it is imperative that composite materials be properly-designed and installed to ensure adequate performance. When composite materials do not perform as designed, the primary cause has often been associated with improper installation techniques. Additionally, with the increased use of composite materials for reinforcing anomalies other than just corrosion, it is important that each repair be properly designed for the loads and conditions to which it will be subjected. Non-corrosion anomalies that have been repaired using composite materials include plain dents, mechanical damage (i.e. dent with gouges), wrinkle bends, bends, branch connections, and girth welds. Through PRCI-sponsored efforts, along with independent investigations sponsored by pipeline operators and composite manufacturers, it is clear that composite materials can provide the required levels of reinforcement to damaged pipelines. Ensuring long-term performance is an essential element of any composite repair design. The key to the successful long-term performance of composite systems is to select high-strength composite materials and install enough material (i.e. proper thickness) to ensure that stresses in the composite material, and the repaired pipeline, during operation are less than design stresses. Standards like the ASME PCC-2 standard, *Repair of Pressure Equipment and Piping, Part 4 Non-metallic and Bonded Repairs*, are used to determine the appropriate composite repair design stresses.

Before selecting a composite material system to repair high pressure transmission pipelines, pipeline operators are encouraged to consider the following recommendations:

- Only those systems demonstrating compliance with the ASME PCC-2 repair standard (or its equivalent European standard, ISO 24817) should be used.
- In addition to the minimum test requirements set forth in ASME PCC-2, testing should also be conducted to address the following:
    - Repair of corrosion subjected to cyclic pressures
    - Measure at design pressures and SMYS (Specified Minimum Yield Strength) stresses in the repair material using strain gages (these measurements known as *inter-layer strain*).
    - Long-term exposure in a buried environment.
- Beyond the repair of corrosion (which is addressed in ASME PCC-2), all additional anomaly repairs must be validated by performance testing. The tests must integrate simulated in situ loading conditions. For example, it is not appropriate for a system to be used to repair dents subjected to cyclic pressure service when the only testing that has been conducted for that particular repair system is associated with the repair of corrosion subject to static burst pressures.

It is recommended that only those composite repair systems that have undergone extensive testing and analysis be considered for use by Dominion. Many of the composite companies participating in the PRCI programs have demonstrated a commitment to providing quality products and a willingness to meet the requirements set forth in the ASME PCC-2 standard. Other systems that have not been subject to rigorous testing may not provide the same level of performance.

The contents of this document provide a brief overview of the composite repair industry including discussions on the ASME PCC-2 standard and how it is used to properly-design a composite repair system. Specific discussions are also provided on using composite materials to repair corrosion and dents, as well as use of composite materials to reinforce features such as branch connections, wrinkle bends, and girth welds. A section has also been included that details a study conducted to evaluate the reinforcement of planar defects in low frequency ERW seams using composite materials.

One of the important findings from the significant body of research that has been that not all composite repair systems perform equally. Full-scale testing has been useful for identifying those systems that are best-suited for the repair of high pressure pipelines. In the absence of adequate testing, it is difficult, if not impossible, to differentiate between the performance of the competing composite repair systems. The primary aim of this document is to assist Dominion in selecting and using composite repair systems that meet the integrity management requirements of their pipeline system.

1.0 INTRODUCTION

For the better part of the past 25 years the pipeline industry has used composite materials to repair corrosion in gas and liquid pipelines. Much of the research associated with the development of composite repair systems has been funded by the gas transmission pipeline industry, with an emphasis on repairing high pressure pipelines. The primary use of composite materials has been to repair corrosion, although research dating back to the mid-1990s has also been conducted for repairing dents and other mechanical damage (the latter being accompanied by grinding to remove any gouges or indications of cracked material). More recently, efforts have been undertaken to evaluate the ability of composite materials to reinforce wrinkle bends, branch connections, elbows/bends, girth welds, and even crack-like features.

This guideline document includes Section 2.0, *Guidance for Operators,* that discusses how to properly use composite repair systems to ensure the long-term integrity of pipeline systems. This section provides instructions on how to properly use composite materials including information on assessing pipeline defects, designing a composite repair system using industry accepted-standards like ASME PCC-2, and proper installation methods and techniques. It has been the observation of the author that having a set of specific requirements that can be enforced through documentation and inspection is essential if composite materials are used to repair high pressure transmission pipelines.

In addition to the *Guidance for Operators* section, this document describes information on repairing defects in pipelines, including external corrosion and dents, using composite materials. The goal for making repairs is to restore strength to the damaged sections of pipe to ensure performance levels are at least as sound as the original pipe. The effects of static and cyclic pressure should be considered in the design of any repair. Additionally, if appropriate, accounting for the presence of external loads (e.g. axial and bending) should be considered, as well as elevated temperatures is they exist in service.

The procedures presented in this document involve the repair of high pressure transmission pipelines using composite materials. Consequently, it is imperative that the recommended installation techniques provided by each manufacturer be followed. The only composite repair systems that should be used are those manufactured by companies with certified training programs, where hands-on installation classes are required for certified installers.

From a design standpoint, any composite repair system that is used to repair a pipeline must demonstrate that it can meet the requirements of industry standards, such as ASME PCC-2 and/or ISO 24817. Composite manufacturers must be able to produce documentation from a third-party organization demonstrating their compliance with these standards, including meeting the required material and performance properties. Additionally, when composite materials are used to repair and/or reinforce anomalies in addition to corrosion (i.e. dents, branch connections, wrinkles, etc.), it is essential that testing be conducted to demonstrate that adequate performance levels can be achieved. Examples are available in the open literature on how these types of qualification programs are accomplished [10, 12].

It is recommended that Dominion have documentation on file that identifies which composite repair systems are approved for use. To be approved composite repair companies should provide certification documents demonstrating their compliance with industry standards, such as ASME PCC-2, accompanied by supporting test results and if appropriate, documentation for the repair of non-corrosion features. <u>With the increasing oversight from regulators the importance of appropriate documentation cannot be overemphasized.</u>

A methodology was developed to assist gas and liquid transmission pipeline operators in evaluating the severity of pipeline defects as part of their overall integrity management programs. This methodology, known as the Engineering-Based Integrity Management Program (EB-IMP®[1]), integrates existing knowledge, analytical techniques, experimental methods, and engineering rigor to develop field-friendly tools to characterize and ensure pipeline integrity [17]. This EB-IMP® program is based in part on the principles embodied in the API 579 Fitness for Service document. At its core, API 579 makes use of a three-level assessment process to evaluate the fitness for service of a particular component or system. Much of this work was driven by the Downstream industries' needs in U.S. refineries; however, there are several sections within this document that are applicable to pipelines including sections on corrosion in field bends and evaluating the effects of dents. EB-IMP® is a five-step process for evaluating pipeline imperfections. Figure 1.1 is a flow chart of the proposed process that builds on the basics assessment phases of API 579, but expands the process by integrating a testing phase (Level IV) and a repair phase (Level V). In the context of composite repairs, the intent in conducting a Level V assessment is to properly design a system to meet the loading requirements associated with a particular anomaly. Provided in Appendix A is a paper on EB-IMP® presented at the 2014 ASME Pressure Vessel & Piping Conference

[1] EB-IMP is a registered trademark of Stress Engineering Services, Inc. (Houston, Texas).

(Paper No. PVP2014-28256) entitled, *Developing an Engineering Based Integrity Management Program for Piping, Pipelines, and Plant Equipment*.

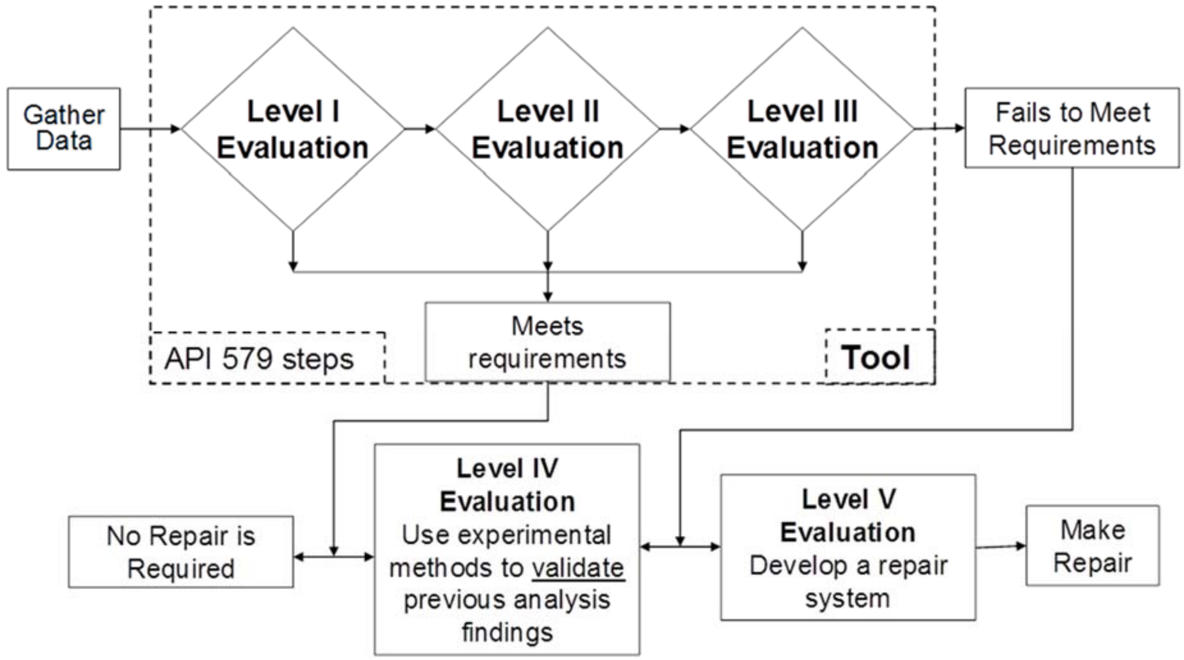


Figure 1.1: Elements of the EB-IMP® process

This *Composite Repair Guideline Document* includes Section 2.0, *Guidance for Operators*, which provides specific details for Dominion to evaluate the design of composite repair systems and ensure they are properly installed. The *Design and Installation of Composite Repairs* section addresses subjects that include material qualification, qualified personnel, installation procedures, and a discussion on the effects of pressure at the time of installation. The *Repair of Defects* sections provides discussions on the repair of corrosion and dents, as well as discussions on reinforcing other features such as wrinkle bends, girth welds, and branch connections. A *Risk Analysis* section is provided to assist Dominion in developing a formal method for conducting a risk analysis on a particular repair, should the need arise for having this level of documentation. Finally, the *Discussion* and *Closing Comments* sections provide discussion on topics such as areas of caution in using composite repairs, inspection of repairs, and record keeping. A *Reference* section and several appendices are also provided.

A final comment is made regarding the motivation behind the development of this guideline document. It is recognized that as a pipeline company Dominion is unlikely to either design or install composite repair systems, with much of this work being completed by manufacturers, suppliers, and installation contractors. However, as a user of composite repair systems, it is important that Dominion be armed with the proper knowledge to ensure that when composite repair systems are used, they are designed and installed to meet the service requirements of the respective pipeline system. It is this recognized need that serves as the basis for the development of this document.

2.0 GUIDANCE FOR OPERATORS

Most of the contents of this guideline document are focused on providing Dominion with background information on the design and assessment of composite repairs. Although it is important that supporting information be a part of documentation maintained by Dominion, an equally important part of this document is guidance for Dominion in understanding how to properly use composite repair systems to ensure the long-term integrity of their pipeline systems. This section of the guideline document has been specifically prepared to provide Dominion with instructions for properly using composite materials. Detailed discussions are included on the following three subjects:

- Assessment of pipeline defects
- Designing a composite repair system
- Proper installation methods and techniques

The above subjects are at the core of making a sound repair. Figure 2-1 is a flowchart showing the basic elements associated with the design and installation of an *optimized repair solution*. <u>For Dominion the key to achieving this condition is to identify the critical aspects required to achieve an optimized repair.</u> In other words, what is acceptable and what is not? In ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix 1, a two-page *Component Repair Data Sheet* is included that is an ideal resource for operators who want to ensure that all facets of the repair have been completed. A copy of this data sheet is included in Appendix B. It is recommended that Dominion either use the ASME PCC-2 data sheet in its current form, or create a similar form, that includes company-specific items as appropriate.

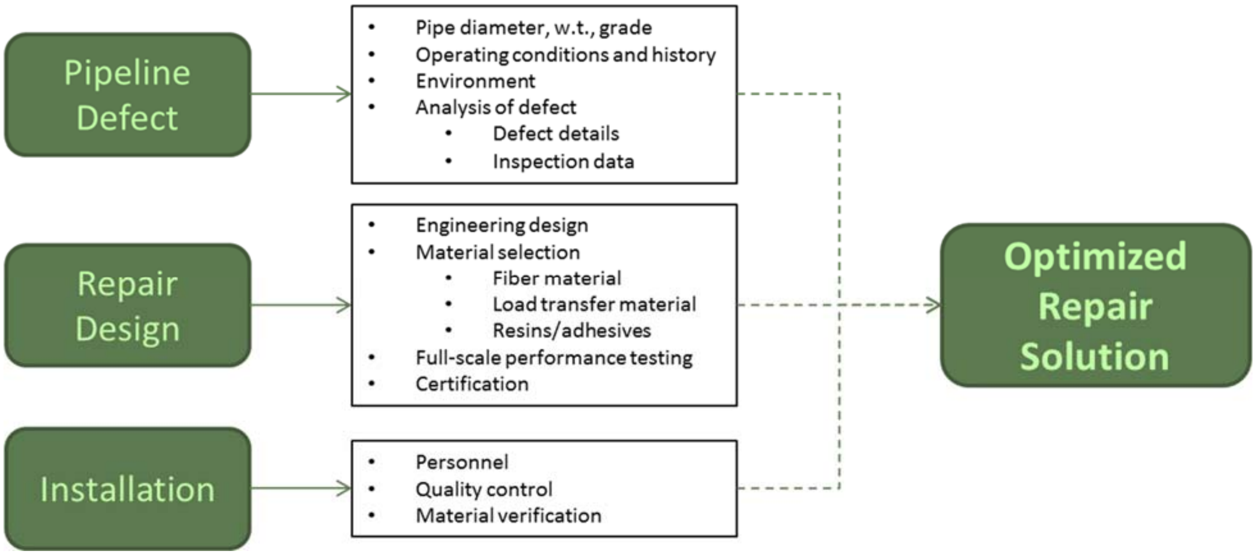


Figure 2-1: Flowchart showing elements for an optimized repair solution

2.1 Assessment of pipeline defects

Before making a pipeline repair, there must be some basis for determining the severity of the pipeline damage and what type of repair is appropriate. This typically involves calculations using data acquired from an in-line inspection tool that has indicated the presence of corrosion, dents, or other pipeline anomalies followed by an in-the-ditch assessment to confirm the actual pipeline conditions. The identified features are analyzed to determine their impact on the integrity of the pipeline. For example, the data required to perform an assessment of corrosion includes pipe diameter, wall thickness, material grade, as well as corrosion depth and length. Standards and guidance documents such as API 579/ASME FFS-1, ASME B31G, or BS7910 are typically used to perform the required calculations for corrosion assessment. If the corrosion severity is of sufficient magnitude, the pressure in the pipeline must be reduced (i.e. de-rated), or a repair is required if the pipeline is to continue operating at the existing Maximum Allowable Operating Pressure (MAOP). Once the severity of the corrosion has been determined, it is a rather straightforward process to determine what is required to repair the corrosion using a composite repair system. The ASME PCC-2 standard (Part 4 Nonmetallic and Bonded Repairs, Section 3 Design) provides very clear direction on repairing corrosion using composite materials, including how to calculate the required thickness and length of the repair.

Although the assessment of corrosion is well understood, it is recognized that the same cannot be said of analyzing other features such as stress corrosion cracking, dents, mechanical damage, gouges, wrinkles, branch connections, girth weld imperfections, and seam weld defects. Analyzing these features typically requires specific techniques using numerical analysis tools like finite element modeling, fracture mechanics, or full-scale destructive testing. Before a composite repair is designed, it is essential that the pipeline defect be properly evaluated to ensure that all facets of the pipeline's operation are taken into consideration. Referring to the ASME PCC-2 document (cf. Appendix B), listed below are a few of the important questions to be captured in the "assessment" process (in addition to the *essential data* listed in the preceding paragraph).

- What is the required lifetime of the repair?
- What measurement details are available on the features to be repaired? Examples include dent depth and length, wrinkle bend height and length, and weld details on an existing weld/saddle reinforcement of branch connections.
- What pipeline loads can be expected including internal pressure and, if appropriate, external bending moments and/or axial loads?
- What is the operating history of the pipeline including pressure data as a function of time (i.e. what is the range of pressure cycles and their associated frequency)?
- What are the expected ambient temperatures of the soil in the vicinity of the repair, as well as the maximum operating temperature of the pipeline?
- How much time has been allocated to make the repair and how much time is available for curing before backfilling?

As when constructing a building, having a proper foundation is essential. The assessment process presented in this document establishes a firm foundation on which to design and install a composite repair solution. Failure to address the appropriate details in the assessment process could result in the development of a non-conservative composite design that fails to properly-reinforce the pipeline.

2.2 Designing a composite repair system

Once an assessment of the pipeline anomaly has been completed and it has been determined that a repair is required, the composite repair system can be designed. It is essential that a composite system used to repair pipelines have the necessary documentation to demonstrate its worthiness. Repair systems should have third party certification from a reputable engineering firm that has evaluated the system based on the requirements of the ASME PCC-2 (or ISO 24817) standard. Additionally, the system must have been subjected to full-scale destructive testing to ensure that the composite system can adequately provide the required level of reinforcement. The is especially true for the reinforcement of features other than corrosion (e.g., dents, wrinkle bends, planar defects, etc.) that are not explicitly addressed in the current composite repair design standards. The list below provides some exemplar test programs performed previously on pipeline features that were repaired using composite materials.

- Reinforcement of branch connections subjected to internal pressure in combination with in-plane and out-of-plane bending loads
- Reinforcement of wrinkle bends subjected simultaneously to internal pressure and axial tension
- Reinforcement of wrinkle bends subjected simultaneously to internal pressure and cyclic bending
- Repair of mechanical damage (dents with gouges) subjected cyclic pressures followed by burst tests
- Reinforcement of defective girth welds subjected to internal pressure in combination with axial tension and bending
- Reinforcement of corrosion subjected to internal pressure in combination with axial tension and bending
- Reinforcement of planar defects in low frequency ERW seams
- Reinforcement of crack-like defects

As in the assessment process, designing a composite system for repairing corrosion is straightforward. ASME PCC-2 provides very clear directives for repairing corrosion, including how to calculate the thickness and length of the repair based on the material properties of the composite repair. Presented in Figure 2-2 are the three calculation methods from ASME PCC-2-2015 for determining the required thickness for repairing a 50% deep and 8-inch long x 6-inch wide area in a 12.75-inch x 0.375-inch, Grade X42 pipe damaged by corrosion. As noted, the calculated thickness of the repair varies from a minimum 0.138 inches to a maximum of 0.787 inches, depending on the selected calculation method. The thickness depends on how much information is known about the material properties of the composite material (i.e. the more that is known about a material the greater the confidence in expected performance, accompanied with a commensurate reduction in the required safety factor). Using a repair thickness of 0.138 inches (the minimum thickness of the three presented values) requires that the manufacturer acquire the most extensive level of data (i.e. minimum test period of 1,000 hours) of the three presented thickness values.

<u>All composite repair manufacturers must have a design package for their particular system that validates the ability of their system to repair corrosion to meet the minimum requirements of ASME PCC-2.</u>

ASME PCC-2-2015 Calculations

Repair of 12.75-inch x 0.375-inch, Grade X42 pipe with 50% corrosion

ASME PCC-2 Equation Number		ASME PCC-2 Equation	Calculated Values (see Note below for variable values)
(3)	Stress-based	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot (P - P_s)$	0.787 inches
(6)	Strain-based	$t_{min} = \frac{1}{\varepsilon_c E_c}\left(\frac{PD}{2} - st_s\right)$	0.306 inches
(12)	1,000 hour test based	$t_{min} = \left(\frac{PD}{2} - t_s s\right) \cdot \left(\frac{1}{f s_{lt}}\right)$	0.138 inches

Notes (input variables used in above equations)

E_s	30×10^6 psi (steel pipe modulus)
E_c	4.5×10^6 psi (composite laminate modulus)
s	42,000 psi (pipe Minimum Specified Yield Strength, or SMYS)
P	1,778 psi (MAOP)
P_s	1,000 psi (de-rated operating pressure due to presence of corrosion)
t	0.375 inches (pipe nominal wall thickness)
ε_c	0.25% (allowable long-term composite strain from ASME PCC-2 Table 4)
f	0.5 (Service Factor from ASME PCC-2 Table 5)
s_{lt}	50,000 psi (long-term composite strength based on ASME PCC-2 Appendix V directives)
t_s	0.188 inches (remaining pipe wall thickness due to corrosion)

Figure 2-2: ASME PCC-2 Calculations for repairing corrosion defects

A few of the important questions to be addressed in the process of designing a composite repair are listed in the bullets that follow.

- In terms of material properties, what is the elastic modulus and short-term tensile strength of the composite material system? Factors that affect performance of the composite material include fiber type, matrix material (i.e. resin), and fiber orientation.
- Has a filler material (i.e. load transfer material) been selected that provides the required level of reinforcement? Has this material been subjected to the required testing regime to ensure that it can withstand the anticipated loading conditions?
- Is material property (filler & composite material system) data available as a function of temperature? Having data on the matrix resin alone is not sufficient for applications where conditions exceed room temperatures (i.e. the environment where tensile test data are typically obtained). A plot showing material strength as a function of temperature should be provided by the manufacturer.
- Has the repair been subjected to the full battery of loads to which it will experience in service? If so, has an appropriate safety factor been applied to ensure that a long-term solution has been achieved?
- What documentation has been provided from the composite manufacturer/supplier? Do they have a certificate from a third-party engineering company demonstrating their compliance with ASME PCC-2?
- What Quality Assurance methods are in place to ensure that what has been designed is being delivered to the end user? Does the manufacturer/supplier have a method for traceability and tracking products?

2.3 Proper Installation Methods and Techniques

Once the assessment and design phases of work have been completed, the final stage of the process involves actual installation of the repair. Properly installing composite materials is an essential element of the repair process. Failure to install the repair properly creates a condition where sub-standard performance of the repair can be expected. The few failures that have occurred with composite repair systems have typically been associated with improper installation techniques, with the primary failure modes being uncured resins, not installing enough composite materials, and insufficient adhesive application. Once a sound repair has been designed, it is possible to put measures in place to ensure that installation failures do not occur.

In ASME PCC-2, Repair of Pressure Equipment and Piping, Article 4.1, Mandatory Appendix VIII, Installation, details are provided on what is required to properly install a composite repair system. A copy of this section is provided in Appendix C: ASME PCC-2 Installation Requirements

that includes items related to surface preparation, laminate lay-up, cure, and documentation. The contents of Appendix C: ASME PCC-2 Installation Requirements

should be reviewed in the context of proper installation methods; however, listed below are several of the key questions that should be addressed when composite materials are installed on pipelines. ADV encourages the involvement of the repair manufacturers/suppliers in the process of answering these questions, including the integration of their experience in repairing pipelines.

- Has the pipeline been properly exposed and has the surface been abrasively blasted to the manufacturer's recommendations? This is typically NACE 2, or a near white metal. Provided in Appendix D: Surface Preparation Standards
- is a document on surface preparation standards.
- Have the right materials been installed for the right job? This embodies the concept that enough composite material has been installed (i.e. thickness and length), as well as ensuring that the correct resin and adhesive materials have been selected and properly mixed.
- What is the working pot life for the adhesives/resins in the system? At what point in the installation process should the adhesives/resins no longer be used? It is essential that a time limit on installation be designated and monitored during application; once resins are removed from their shipping containers and mixed, they have a limited pot life.
- During installation, how important is it to keep debris (i.e. sand and soil) away from the installation site? Additionally, in the event of inclement weather (cold, snow, rain, etc.) how should the repair be protected?
- How much cure time is required before the ditch can be re-filled and the line can be placed back in service?
- What measurements can be taken to ensure that all adhesives and resins have cured properly?
- If the repairs are made in an area with saturated soils, have precautions been made to ensure that an unacceptable level of moisture ingression does not take place?
- Have the personnel making the repair been properly trained? Do they have the necessary certification to demonstrate their training?

- Who is responsible for signing off that the repair has been properly made (i.e. Certified Installation Reviewer – field inspector)?
- Does the Certified Installation Reviewer have a checklist to verify that the repair has been completed according to the appropriate specification? If so, has the checklist been completed and properly documented? Refer to ASME PCC-2, Article 4.1, Mandatory Appendix VIII, Section VII-5 Documentation, for details on the subject of required documentation.
- Is it possible to stop the repair process for a period of time and then go back and install additional material?
- What are the pot and working lives of the filler (i.e. load transfer) material?
- Is there a time that is required between the installation of the filler material and the composite material?
- Are there service temperature limits during installation?

2.4 Assessment of Existing Composite Repair Technologies

This section of the guideline document has been prepared concerning ASME PCC-2 certificates of compliance that have been issued by the author for different composite repair technology companies. Provided below are details associated with this effort that include a list of the companies and their associated technologies receiving certification. In addition to the provided ASME PPC-2 certification list, a section has also been prepared identifying the various technologies that have participated in the 15 Joint Industry Programs that have been co-funded by organizations including Pipeline Research Council International, Inc. (PRCI), the Bureau of Safety and Environmental Enforcement (BSEE), the Pipeline and Hazardous Material Safety Administration (PHMSA), ROSEN, and the composite manufacturers.

2.4.1 ASME PCC-2 Certifications

As discussed previously, the ASME PCC-2 document (and its ISO 24817 counterpart) provide a basic framework for establishing the minimum requirements for any composite repair technology, especially those designed to repair high pressure pipelines. Recognizing the rigorous requirements associated with the repair of regulated high-pressure pipelines, two additional tests beyond the testing required by ASME PCC-2 have been recommended to industry by the author. These two tests are the inter-layer strain test and cyclic pressure fatigue test that are descried below:

- The inter-layer strain test[2] involves the installation of strain gages between layers of the composite repair, typically every 2 to 3 layers. The repair is on the reinforcement of a 75% deep corrosion samples (cf. Figure 4-1) and the thickness of the repair is based on the respective technology's ASEM PCC-2 design. During pressurization to failure, strain gages are monitored in the corrosion defect region, as well as the gages installed between the layers to monitor the inter-layer strains. The important benefit in conducting this test is quantifying the strains (or stresses, calculated as the product of strain and the composite material's elastic modulus) at design conditions (72% SMYS) and 100% SMYS. Based on previous testing, all composite repair designs meeting the requirements of ASME PCC-2 have measured stresses (based on inter-layer strain measurements) that are less than the designated composite design stress, which is typically 0.5 times the long-term design stress, s_{lt}. This test has been instrumental in validating the long-term performance of composite repair systems and has also been used to demonstrate compliance for regulatory bodies in both the U.S. and Canada.
- Like the inter-layer strain test, the *pressure cycle fatigue test* is an important test used to demonstrate the performance capabilities of the respective composite design. The repair is on the reinforcement of a 75% deep corrosion samples (cf. Figure 4-1) and the thickness of the repair is based on the respective technology's ASME PCC-2 design. The sample, which is typically fabricated using 12.75-inch x 0.375-inch, Grade X42 pipe material (12-inch NPS STD), is pressure cycled to failure at a pressure range from 36% to 72% SMYS (890 to 1,780 psi for the 12-inch NPS STD pipe). The number of cycles to failure is recorded. Approximately 20 different composite systems have been tested since 2005, with cycles to failure ranging from approximately 20,000 cycles to 750,000 cycles.

While not required by ASME PCC-2 or ISO 24817, these two tests are useful to validate the performance of composite repair systems used to reinforce high-pressure pipelines. This is especially true for pipeline systems regulated by PHMSA and Canada's National Energy Board. On several occasions the author has been called upon by pipeline operators to interface with these regulatory agencies and the additional

[2] The measurement of inter-layer strain using strain gages is not a requirement in ASME PCC-2. It is merely another means for quantifying performance. The stresses computed based on inter-layer strain measurements for all systems meeting the requirements of ASME PCC-2 have all been less than the ASME PCC-2-designated design stresses. Indirectly, the inter-layer strain testing has validated the technical validity in using ASME PCC-2 as a design standard.

testing was useful for demonstrating the long-term performance of the composite technologies under review.

Listed below are the composite technologies and the respective manufacturers who have received certifications issued under the oversight of Dr. Chris Alexander, PE.

- Armor Plate MP System
- Armor Plate ZED System
- Armor Plate EXT System
- Fyfe Tyfo®Fibrwrap® SCH-41-1X System
- Milliken A+ System
- Milliken Atlas CFE System
- NRI Steel-Wrap E System
- Western Specialties' Composi-Sleeve™ System
- Western Specialties' Ultra-Wrap™ System
- WrapMaster's PermaWrap System

It should be stated that the absence of a composite repair system from the above list does not preclude its technical worthiness and the presentation in the above list is not intended to discourage the use of sound repair technologies. However, the author is not able to provide the same level of first-hand knowledge for systems not listed above. The absence of the inter-layer strain and cyclic pressure data are typically what differentiate the above technologies from those not listed. Dominion is encouraged to request inter-layer strain and cyclic pressure test results from any manufacturer seeking approval for installation of their technology on Dominion's pipeline system.

2.4.2 Joint Industry Programs

Since 2005, 15 Joint Industry Programs (JIPs) have been organized involving full-scale destructive testing as a means for qualifying and evaluating composite repair technologies used to reinforce a wide range of pipeline anomalies, features, and operating conditions. Listed below are the titles of the programs, along with the sponsoring organizations. Table 2-1 provides a list of the manufacturers who participated in each of the studies (only manufacturers have been listed and not specific composite repair systems).

In addition to the testing efforts, two literature studies have been sponsored by PRCI including the MATR-3-3, *State-of-the-art Assessment*, and MATR-3-10, *Composite Repair Guideline Document*, studies. Further, PRCI commissioned ESR Technologies under the technical oversight of Mr. Richard Lee to conduct the NDE-2-3 study focused on evaluating various inspection techniques applied to composite wrap repairs. Also included in the list are five studies conducted by pipeline operators and the papers presented at the International Pipeline Conference that provide results of the studies.

1. PRCI MATR-3-4 Buried Pipe Corrosion Reinforcement Pipe Study (3-year and 10-year)
2. PRCI MATR-3-5 Dent Reinforcement Study
3. PRCI MATR-3-6 Vintage Girth Weld Reinforcement Study
4. PRCI MATR-3-7 Subsea Reinforcement 10,000-hr Study
5. PRCI MATR-3-9 Re-rate Study
6. PRCI MATR-3-11 Load Transfer / Effects of Pressure
7. PRCI MATR-3-12 Inspection of Delamination and Disbondment Defects
8. PRCI MATV-1-2 Wrinkle Bend Study
9. Minerals Management Service (MMS)[3] Offshore Study
10. Composite Manufacturer-sponsored *Dent Validation Collaborative Industry Program* (DV-CIP); in partnership with in-line inspection efforts provided by ROSEN
11. Composite Manufacturer-sponsored Crack Reinforcement
12. Composite Manufacturer-sponsored Effects of Installation Pressure
13. Composite Manufacturer-sponsored Crack Arrestor
14. Composite Manufacturer-sponsored Wrinkle Bend
15. BSEE 10,000-hr Offshore Study (reinforcement of corrosion in a subsea environment)
16. PHMSA Onshore Study (i.e., topics like cyclic pressure and effects of pressure during installation)
17. Operator Study: El Paso Wrinkle Bend Reinforcement Program (IPC2008-64039)
18. Operator Study: Chevron High Temperature Program (IPC2016-64211, 64213, and 64214)
19. Operator Study: Large Diameter Elbow Reinforcement Program (IPC2016-64311)
20. Operator Study: Alyeska Pipeline Filler Material Assessment Program (IPC2016-64104)
21. Operator Study: Boardwalk Pipeline Reinforcement of LF ERW Pipe Program (IPC2016-64082)

[3] The Minerals Management Service (MMS) was an agency of the United States Department of the Interior (U.S. DOI) that managed the nation's natural gas, oil, and other mineral resources on the outer continental shelf. MSS started in 1982 and was dissolved in October 2001. Today BSEE functions as the organization carrying out many of the functions that MMS was originally commissioned to conduct.

Table 2-1: Summary of Participants in Industry-wide Studies

Sponsoring Organization	Program Description	Composite Manufacturers													
		Armor Plate	Air Logistics	Clock Spring	Citadel	EMS Group	Furmanite	Milliken / Pipe	Neptune Research	Pipestream	T.D. Williamson	Walker Technical	Wrap Master	Western	3X Engineering
Pipeline Research Council International Programs († co-sponsored with composite manufacturers)															
PRCI	MATR-3-4: Buried Corrosion Reinforcement (†)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
PRCI	MATR-3-5: Dent Reinforcement Study (†)	✓	✓		✓		✓			✓			✓		
PRCI	MATR-3-6: Vintage Girth Weld Reinforcement (†)	✓			✓			✓						✓	
PRCI	MATR-3-7: Subsea Reinforcement Study (†)	✓							✓			✓			
PRCI	MATR-3-9: Re-rate Study (†)									✓					
PRCI	MATR-3-11: Load Transfer / Effects of Pressure (†)	✓			✓		✓		✓					✓	
PRCI	MATR-3-12: Inspection of Defects			✓			✓	✓					✓		
PRCI	MATV-1-2: Wrinkle Bend Study (†)	✓													
Composite Manufacturer Sponsored Programs															
Mfg.	Dent Validation Collaborative Industry Program	✓	✓												
Mfg.	Crack Reinforcement (2 programs)	✓	✓		✓		✓	✓	✓					✓	
Mfg.	Crack Arrestor				✓		✓	✓	✓					✓	
Mfg.	Wrinkle Bend	✓	✓		✓			✓	✓					✓	
Mfg.	Effects of Installation Pressure	✓			✓		✓		✓					✓	
Regulatory Agency Sponsored Programs															
MMS	Corrosion Study	✓	✓					✓							
BSEE	Offshore 10,000-hour Corrosion Study	✓			✓				✓						
PHMSA	Cyclic Pressure / Effects of Installation Pressure								✓					✓	
SUM of PARTICIPATION:		**12**	**6**	**2**	**9**	**1**	**7**	**7**	**9**	**3**	**1**	**2**	**3**	**8**	**1**

Listed below are companies whose technologies have been evaluated by the author. It cannot be emphasized too strongly that only composite repair technologies having met the minimum requirements of ASME PCC-2 or ISO 24817 be used.

- Air Logistics
- Armor Plate, Inc.
- Clock Spring
- Citadel Technologies
- EMS Group
- Pipe Wrap, LLC
- T.D. Williamson, Inc.
- Walker Technical
- Wrap Master
- 3X Engineering
- Furmanite
- NRI
- Pipestream
- Western Specialties

2.4.3 Threat Based on Anomaly Type

As demonstrated in this report, a significant body of work has been conducted to support the use of composite materials in reinforcing high pressure transmission pipelines. The information presented in Table 2-1 summarizes the supporting research. In a complimentary manner Table 2-2 is an assessment matrix based on anomaly type that reflects three factors including field experience, guidance provided in industry standards, and previously-conducted independent research. It is recognized this assessment is somewhat subjective; however, operators are cautioned in using composite materials to reinforce anomalies indicated as either having all **RED** cells or not having at least one **GREEN** cell. The information in this table helps identify where the knowledge gaps exist when considering composite repair technologies.

Over the past 25 years the author has evaluated more than 40 different composite repair technologies. As one might expect, varied performances have resulted with some technologies performing better than others. Further, many of the composite repair companies have multiple technologies; one company might have a top-performing carbon-epoxy system, although their E-glass technology might be average. In this regard it is important for operators to understand the technical capabilities of each company and system, but equally important to identify technology limitations.

Provided in Table 2-3 is a Composite Repair Threat Matrix. This table combines information in Table 2-1 that provided a summary of composite technologies that participated in the pipeline industry's joint industry studies. Listed in Table 2-3 are anomalies common to transmission pipelines.

Assigned to each anomaly in Table 2-3is guidance as to whether the repair can be made, classified as:

- Acceptable repairs
- Repairs should be made with caution
- Repairs not recommended

Notes have also been included to provide specific information on each respective anomaly or feature. For anomalies and features not included in this table, an engineering assessment including full-scale testing with supporting numerical analysis can be used to validate a specific composite repair design. Several of the repairs listed in this table were made possible by extensive research and development efforts conducted by pipeline operators, regulatory agencies, and composite repair manufacturers; examples include the reinforcement of plain dents, wrinkle bends, low frequency ERW seams, vintage girth welds, and large diameter elbows subject to bending and internal pressure loading.

Table 2-2: Composite Repair Guidance and Experience Based on Anomaly Type

Pipeline Anomaly, Technical Issue, or Feature	Actual Field Experience	Guidance from Standards (ASME & ISO)	Independent Research
External corrosion in straight pipe <80% (Non SBD)	Green	Green	Green
Plain dents subjected to cyclic pressure (PCC-2 appendix is being developed based on PRCI data)	Green	Yellow	Green
Dents with metal loss subjected to static/cyclic pressure	Red	Red	Yellow
Dents in welds (seam and girth) subjected to cyclic pressure	Yellow	Red	Green
Dents with gouges	Green	Red	Yellow
Seam weld defects including low frequency ERW seam welds	Yellow	Red	Yellow
Vintage girth welds (pressure, tension, bending) including cracks	Yellow	Red	Green
Wrinkle bends	Green	Red	Green
Reinforced branch connections (above and below ground)	Green	Red	Green
Elbows and bends	Green	Yellow	Green
Forged Tees	Green	Yellow	Green
Subsea Diver Applied installations	Green	Red	Yellow
Diverless Subsea Installations	Red	Red	Red
Internal corrosion (non-leaking)	Yellow	Yellow	Yellow
External Stress corrosion cracking (SCC) (w/o grinding)	Yellow	Red	Yellow
External Stress corrosion cracking (SCC) (with grinding)	Green	Red	Yellow
General Corrosion loss > 80%	Yellow	Red	Green
Pitting >80% combined with uniform corrosion <80%	Red	Red	Red
Uprating (re-rating) pressure / Establishing MAOP	Red	Red	Yellow
Effects of pressure during installation	Red	Yellow	Yellow
Repair of leaks after shutdown	Yellow	Yellow	Yellow
Live Repair of leaks (stopgap leak repair incorporated into composite repair)	Yellow	Red	Yellow
Effects of cyclic pressure on corrosion (fatigue design)	Green	Red	Green
Performance at elevated temperatures (Threshold temperature open for discussion)	Yellow	Yellow	Green
NDE Techniques and Defect Acceptance Criteria to look at Composite Material	Red	Red	Yellow
NDE techniques to examine substrate below composite when ILI is not possible	Red	Red	Yellow
Inspection to evaluatre load transfer & delamination / disbondment	Yellow	Yellow	Yellow
Validation of PCC-2 Design for High Grade Steels (X65+)	Red	Red	Red
Detection of composite repairs by ILI	Green	Red	Red
Composite crack arrestors for high pressure gas pipelines	Yellow	Red	Green
QA/QC Requirements - understand the impact of deviations in installation. Human Dimension & Training	Yellow	Green	Yellow
Improve buckling resistance of pipes subject to geohazards	Red	Red	Yellow

Color Code	
Green	Work performed in this area
Yellow	Moderate/limited experience
Red	Minimal to no experience

Table 2-3: Composite Repair Threat Matrix

Anomaly / Feature	Notes
ACCEPTABLE REPAIRS	
External corrosion (< 80%)	Well-documented with design based on ASME PCC-2, caution if cyclic pressure present. *Any composite repair system meeting the requirements of either ASME PCC-2 or ISO 24817; operators are discouraged from using systems that do not meet the requirements of either of these standards. If cyclic pressure is present testing should be conducted to ensure an acceptable design life of the repair exists.*
Plain dents	Well-documented with significant supporting research. *Most composite repair systems meeting the requirements of ASME PCC-2 or ISO 24817 should be adequate for reinforcing dents; however, the following manufacturers have tested composite technologies relative to the severe dents tested in PRCI's MATR-3-5 dent study: Armor Plate, Air logistics, Citadel, Furmanite, NRI, and WrapMaster. Milliken, T.D. Williamson, Walker Technical, and Western Specialties also have technologies that would be expected to perform well. Finally, Clock Spring was tested for reinforcing dents by GRI in the 1990s, although the dents in that program were not as severe as those associated with the PRCI MATR-3-5 study.*
Wrinkle bends	Well-documented with supporting research, axial reinforcement critical. *The following companies have evaluated their technologies for reinforcing wrinkle bends; however, technology performances in testing were varied. It is recommended that prior to using the following technologies these companies be contacted regarding the performance of their respective technologies and the basis of their designs: Armor Plate, Air Logistics, Citadel, Milliken, NRI, and Western Specialties.*
Dents with metal loss	Limited testing, but effective repairs can be designed. This feature category includes corrosion. *Refer to response for "Plain dents".*
Dents with gouging	Validated by testing, gouging should be removed by grinding to achieve a smooth profile. *Refer to response for Plain dents.*
Vintage girth welds	Validated by testing, including tension and bend testing. *The following companies participated in PRCI's MATR-3-7 girth weld study (50% lack of penetration defects): Armor Plate, Air Logistics, Citadel, Milliken, and Western Specialties. Several other composite repair companies have technologies that should perform well; however, their designs need to be validated by testing.*
Elbows and bends	Extensive testing with supporting research, requires supporting design calculations. *There are several composite repair companies having technologies that should perform well with this type of reinforcement; however, to date only Armor Plate has undergone testing funded by a major transmission pipeline operator to evaluate this reinforcement type and its design configuration, including external bending loads.*
Tees	Validated by testing, effective repairs can be designed. *There are several composite repair companies having technologies that should perform well with this type of reinforcement; however, to date only Armor Plate has undergone testing to evaluate this reinforcement type and its design configuration, including external bending loads.*
Welded branch connections	Limited testing including in-plane and out-of-plane bending, effective repairs can be designed. *There are several composite repair companies having technologies that should perform well with this type of reinforcement; however, to date only Armor Plate has undergone testing funded by a major transmission pipeline operator to evaluate this reinforcement type and its design configuration, including external bending loads.*
REPAIRS SHOULD BE MADE WITH CAUTION	
External corr (> 80%)	Only consider if system has been validated by testing
Internal corrosion	Only consider if corrosion rate known, or corrosion has been arrested.
Seam weld planar defects	Limited testing on actual low frequency ERW pipe material, but effective repairs can be designed. *The most extensive body of testing has been conducted on Milliken's Atlas carbon-epoxy system; however, testing on crack-like defects has also been testing on carbon technologies manufactured by Armor Plate, Citadel, Furmanite, NRI, and Western Specialties' CompoSleeve™ system.*
Stress corrosion cracking	Extensive testing on simulated cracks, but effective repairs can be designed. *Refer to response for "Seam weld planar defects".*
Selective seam corrosion	Extensive testing on simulated cracks, but effective repairs can be designed. *Refer to response for "Seam weld planar defects".*
Elevated temperatures (> 120°F)	Repairs should only be made using validated technologies; post-curing typically required. *A comprehensive study evaluated the performance of technologies manufactured by Furmanite, Milliken, and Walker Technical at 250°F for 10,000 hours. Only composite technologies that have undergone extensive elevated temperature testing should be used. Armor Plate also has a high temperature system that has undergone testing.*
REPAIRS NOT RECOMMENDED	
Thru-wall defects	Insufficient research at the present time to support use for transmission pipelines.

3.0 DESIGN AND INSTALLATION OF COMPOSITE REPAIRS

The preceding section, *Guidance for Operators*, provides direction for Dominion in how to evaluate whether or not a composite repair system has been designed and properly installed to meet service requirements. The *Guidance for Operators* section can be used as a stand-alone section; however, it is recognized that additional details are useful to address other aspects associated with the use of composite repair systems. For this reason, this section of the document, *Design and Installation of Composite Repairs*, has been prepared to address the four following elements:

1. Certified materials and products that have been properly designed for the respective repair.
2. Qualified personnel to install the composite materials.
3. Installation procedures provided by the manufacturer.
4. Proper installation conditions and pipe surface preparation.

The sections that follow provide specific details on the above elements. Also included are comments on above ground repairs and addressing the effects of pressure during installation.

3.1 Materials and Products

Material performance is central to every successful composite repair. It is essential that all polymer-based materials be used before their prescribed expiration dates and within the permissible environmental conditions (i.e. temperature, moisture, etc.). It is also essential that the composite materials be able to withstand operating and in-service environmental conditions. Listed below are the materials and products that are required for a typical composite repair. It should be noted that some variations in materials will exist depending on the manufacturer and particular repair system.

1. Filler, or load transfer, material (typically a two-part epoxy putty).
2. Primer material (typically a two-part epoxy).
3. Composite cloth or fiber material (typically an E-glass or carbon fiber system).
4. Composite resin (for a *pre-preg* system, the resin is pre-impregnated into the cloth; while for *field applied* systems the resin is installed locally at the installation site).

As appropriate, each material should have a Safety Data Sheet (SDS) that includes pertinent information on the respective materials in the system including resins, adhesives, and the load transfer (i.e. filler) material.

From a quality control standpoint all suppliers should have paperwork that verifies the materials used in the repairs are identical to those associated their particular design. Quality control documentation should be provided for all materials supplied as part of the system. This should include traceability by batch or lot number to quality control test results of the critical components (i.e. resins and filler material). Documentation on the design basis of the repair should also be available for review upon request.

3.2 Qualified Personnel

Before an individual is allowed to install a composite repair, they should complete a training course and demonstrate a minimum level of proficiency as required by the manufacturer. Certified installers should be able to do the following:

- Have a copy of the repair system application instruction procedure quality control requirements on hand during installation for reference.
- Identify the critical activities associated with a proper installation and know when an improper repair has been made.
- Personnel need to know how to apply the materials (e.g. brush or scraper), how to obtain proper wetting on the pipe and fiber mat, and judge/measure the result for compliance with a composite repair standard.
- Be familiar with the concepts associated with “pot life” and “shelf life.”
- Understand why it is important that the proper thickness of composite material be installed on a pipeline having corrosion (or other defects).
- Be able to distinguish between cured and uncured adhesives and resin systems.
- Be able to perform all quality control functions specified in the application procedure.
- Finally, installers need to be armed with sufficient information and training so they can know when something is wrong and needs modification. Examples include issues associated with resin cure and installation thickness.

3.3 Installation Procedures

Properly installing a composite repair system is essential to ensure that the system performs as designed. It is recognized that various application techniques exist for different composite repair systems. The installation procedures provided below are general in nature, although the approach is directed more towards the use of wet wrap systems. As appropriate, quality control measurements and documentation of results should accompany specific stages of the installation procedure.

There are two phases involved in obtaining an adequate result. The first phase involves properly documenting the condition of the pipeline being repaired. This can be accomplished before the repair team arrives on site, by a separate group, or properly trained personnel can be incorporated into the repair team. Often, blasting is required to properly exposure the condition of the pipe so that minimal additional work may be required by the applicator before the repair is made.

3.3.1 Phase One: Examine and document the pipe to be repaired

1. Inspect the region to be repaired to ensure that no cracks are present in the pipe. If necessary, confirm using an appropriate NDE technique, such as magnetic particle.
2. Confirm the level of corrosion in terms of depth and length. It is assumed that prior to making the decision to make a repair that previous measurements have been made.
3. Provide measurement results of the anomaly to the repair provider to determine the appropriate composite repair design.

3.3.2 Phase Two: Make the repair

1. Determine (or confirm) the appropriate composite repair thickness based on the measured corrosion damage and expected operating/design conditions. The length of the composite repair should extend at least 2 inches beyond extent of the corrosion damage in the longitudinal direction.[4] Section 3.4.8 of ASME PCC-2, Part 4 – Article 4.1, provides additional guidance on repair length.
2. Before installation of the composite material, ensure that the surface has been properly prepared (see the *Pipe Surface Preparation* section of this document).
3. For mechanical damage and dents additional steps may be required before the installation of the repair system, including grinding to remove stress risers.
4. Prepare the work surface where all mixing and preparation of the composite materials is to take place.

[4] Testing has indicated that the length of a composite repair might be more important than originally thought. For the same defect type, composite materials that were 18 inches in length outperformed 12-inch long repairs when considering the repair of corrosion and dents subjected to cyclic pressures conditions.

5. Mix the filler material, also known as the *load transfer material* (typically a two-part epoxy putty). Fill the damaged region of the pipe with the filler material. Trowel the surface of the filler material to ensure that its surface is contoured with the outside surface of the pipe. Rigid repair systems require additional care to fill all the void and area along the DSAW weld cap when applying the filler material.
6. Manufacturers should address the subject of "retained samples" where mixed resins and filler materials at the installation site are placed in a container and saved (i.e. retained). If this is to be done, there should be a consistent methodology based on either number of samples (e.g. 1 for every 100 repairs) or based on a designated time period (e.g. one every two weeks).
7. Mix the resin to coat the outside surface of the pipe (typically a two-part epoxy). Thoroughly cover all the repair region of the pipe, extending as appropriate beyond the extent of the corrosion damage.
8. As prescribed by the manufacturer, prepare the composite material for installation. Pre-preg (i.e. pre-impregnated materials where the resin has been applied to the cloth prior to installation) systems require water to activate the resin (i.e. water-activated urethane); however, field applied systems require saturation in the field, typically using a two-part epoxy.
9. Install the proper number of composite layers on the pipe. The composite material should be pulled tight during installation to ensure that no wrinkles or bubbles are present. Proper overlap should be maintained Continue wrapping until all designated layers are installed. It is essential that the manufacturer's recommendations be followed as prescribed, especially with regards to orientation of the fibers, overlapping, and staggering techniques of the fiber mat.
10. If required, install a ferrous element or metal banding to permit detection by future in-line inspection tool runs.
11. Once all of the composite layers have been installed, the exposed edges and ends of the composite repair should be sealed with an epoxy putty (likely, similar to the one used as the filler material) or other equivalent coating material. Many pipeline companies also install a coating over the outside of the composite repair to protect the material from moisture ingression.
12. It is recommended that certified/qualified personnel remain on-site until sufficient level of the curing has occurred. This includes monitoring for sag on the bottom portion of the repair during a horizontal application, or slide on a vertical application.

13. The final inspection and documentation of the installation should be complete before the ditch is back filled. Allow the composite materials to cure to an acceptable level before backfilling the ditch. A Shore D hardness on the order of 80 is recommended.[5]

3.4 Pipe Surface Preparation

Prepare the repair area surface by abrasive blasting, hand tool cleaning, or power tool cleaning. The best surface preparation is abrasive blasting as it prepares the pipe to a near white metal finish (NACE 2) with a 2 to 3 mil anchor pattern (should be specified by operator). For hand tool and power tool cleaning, remove all loose dirt and debris, rust, and other contaminants that reduce adhesion. A roughened, clean surface is necessary to properly install any composite repair system and ensure that corrosion does not develop beneath the repair. The area prepared for the composite installation must extend at least two (2) inches beyond the extent of the corrosion defect (specific details can be found in ASME PCC-2, Part 4, Section 3.4.8, *Axial Length of Repair*). The minimum length of a repair should be specified and the length of a nonstandard repair should be designated on the repair procedure. If possible, the area of the pipe to be wrapped should be thoroughly wiped with Acetone, MEK, Xylene or equivalent solvent.

3.5 Above Ground Repairs

This document is primarily aimed at repairing buried pipelines; however, it is recognized that some pipeline systems are located above ground. Comments are provided below for addressing issued specific to above ground piping.

- After a composite repair has been made on an above ground pipeline; a top coat (urethane or appropriate paint) should be applied over the composite repair to provide additional protection from ultraviolet (UV) rays.

[5] Shore Hardness is a measure of the resistance of a material to penetration of a spring-loaded needle-like indenter. Hardness of polymers (e.g., rubbers, plastics) is usually measured by Shore scales. Two different indenter shapes and two different spring loads are used for the two Shore scales (A and D). Shore A scale is used for testing soft elastomers (rubbers) and other soft polymers, while Shore D is used for hard polymers like epoxies. Shore Hardness is tested with an instrument called a Durometer that utilizes an indenter loaded by a calibrated spring. The measured hardness is determined by the penetration depth of the indenter under the load. The loading forces of Shore A and Shore D are 1.812 lbs. (0.82 kg) and 10 lbs. (4.54 fg), respectively. Maximum penetration for each scale is 0.097 – 0.10 inches; the Shore Hardness scales range from 0 (minimum hardness) to 100 (maximum, or zero penetration).

Some examples of Shore D hardness include: Shopping cart wheel (Shore D 50) | Golf ball (60 Shore D) | Metal forming wiper dies (70 Shore D) | Hard Hat (80 Shore D).

- Perform a visual inspection as part of the mechanical integrity program annually.
- If the composite material has been subjected to some level of physical impact, an additional visual inspection shall be performed to inspect for evidence of impact damage or other deterioration.
- Visually inspect for any deterioration of the outer wrap of the repair due to UV rays. Any evidence of voids at the edges of the repair next to the pipe surface that would allow moisture & oxygen to penetrate under the composite should be repaired.
- If there are any questions regarding repair, contact the mechanical integrity coordinator and/or composite manufacturer for further investigation and repair determination.

3.6 Effects of Pressure during Installation

The pressure level during installation of the composite material should lowered to ensure safety in accordance with company guidelines, and should be no higher than <u>60% of the estimated failure pressure of the flaw</u> or <u>80% of the current operating pressure</u>; **whichever is lower**. Because the elastic modulus for most composite materials is relatively low in comparison to the modulus of steel, the mechanical reinforcement benefits associated with reducing the operating pressure are not significant for most corrosion repairs. However, if the pressure is not reduced during installation the composite material does not fully-engage until the installation pressure is exceeded. This is a valid and sufficient reason to lower the operating pressure during installation. In addition to the improvements associated with lowering the pressure during installation, there are additional safety benefits for personnel when internal pressure levels are reduced when working near a live pipeline.

In 2015 testing was performed to evaluate the effects of pressure on the reinforcement of relatively severe plain dents (i.e. initial depth on the order of 15% of the pipe's outside diameter, which re-rounded to approximately 3% after pressurization to 72% SMYS). The results of this study, which have not been disclosed publicly at this point, is that pressure present during installation of the composite material can impact the ability of the composite to reinforce a severe dent. The primary difference between corrosion and features, such as dents, concerns the level of deflection in the anomaly that results with changes with internal pressure. In situations where significant re-rounding or deflection of a pipeline feature is likely to occur due to changes in pressure, operators should pay special attention to the effects of pressure during installation. Because as a gas pipeline operator Dominion does not have pipelines that experience aggressive pressure cycling, the effects of pressure during installation on dents should not be an issue.

4.0 REPAIR OF DEFECTS

The preceding section has provided information on the proper design and installation of composite repair systems. This section addresses some of the specific aspects associated with repairing particular anomalies. Included are discussions on repairing corrosion and dents. Additionally, a brief discussion is provided on repairing and reinforcing other features such as girth welds, wrinkle bends, and branch connections.

4.1 Repair of Corrosion

This section of the document provides details on prior and ongoing studies to evaluate the performance of composite materials used to repair corrosion. One of techniques involves the use of strain gages installed on the test samples beneath the composite reinforcement in the machined corrosion region. The reason for acquiring strain measurements beneath the composite materials is to evaluate the level of reinforcement that they provide, with a specific interest in determining if the hoop strain in the pipe remains below an acceptable level. Although there is no designated "acceptable" hoop strain level in a composite reinforced pipe section, it is possible to utilize strain measurements to assess the long-term viability and performance of the repair in light of pipeline operating conditions (i.e. pressure history). Fundamentally, the success of a composite repair is related to its ability to ensure that the damaged section of pipe is able to function per its required service conditions.

In addition to evaluating the integrity of the reinforced pipe material via strain gages installed on the pipe, it is also possible to measure strains within the composite material itself. The benefit associated with this technique is that the measured stress in the composite material can be compared to an allowable composite design stress. There are allowable design stresses (and strains) for composite materials based on the requirements designated in ASME PCC-2, *Repair of Pressure Equipment and Piping*. For purposes of this discussion, the stress limit will correspond to the long-term design stress designated in ASME PCC-2 based on 1,000-hr testing or one of the other long-term testing programs outlined in ASME PCC-2, Article 4.1, Appendix V: *Measurement of Performance Test Data*).

4.1.1 Pressure Cycle Testing of Corroded Pipes

While burst testing pipe samples having simulated corrosion is the fundamental basis of any composite repair assessment program, an equally important testing effort to evaluate long-term performance of the repair involves pressure cycling. Pressure cycle testing has been conducted on numerous composite-reinforced 12.75-inch x 0.375-inch, Grade X42 pipe samples having 75% deep corrosion. The samples were pressure cycled from 36% to 72% SMYS (i.e. pressure range of 36% SMYS). Refer to the schematic diagram provided in Figure 4-1 for details on the test sample. As of the current time, thirteen different composite repair systems have been tested in this capacity. Fatigue life results are provided below for the tested systems, with the minimum and maximum values noted.

- E-glass system: 19,411 cycles to failure (MIN)
- E-glass system: 32,848 cycles to failure
- E-glass system: 129,406 cycles to failure
- E-glass system: 140,164 cycles to failure
- E-glass system: 165,127 cycles to failure
- Carbon system (Sample A: 0.390 inches – Belzona filler): 212,888 cycles to failure
- E-glass system: 223,233 cycles to failure
- Carbon system (Sample B: 0.590 inches – 911 filler): 256,344 cycles to failure
- High-modulus carbon system: 250,000 cycles to failure (run out, no failure)
- E-glass system: 259,537 cycles to failure
- Carbon system: 320,000 cycles to failure (run out, no failure)
- Carbon system: 372,874 cycles to failure
- Carbon system (Sample C: 0.660 inches – 911 filler): 532,776 cycles (run out, no failure)
- Hybrid steel/Epoxy system: 655,749 cycles to failure
- Hybrid steel/E-glass urethane system: 767,816 cycles to failure (MAX)

Other than Samples A, B, and C that were all reinforced using the same carbon-epoxy system, no composite thicknesses have been included in the above list, or material property data such as the elastic modulus. It is widely-recognized and has been validated experimentally that composite stiffness (i.e., product of thickness and elastic modulus) has a direct bearing on the ability of the composite material to reinforce anomalies. This is clearly observed when comparing the results for Samples B and C, where Sample C has a fatigue life that that was 2.1 times the fatigue life of Sample B, even though it was only 12 percent thicker.

Figure 4-2 and Figure 4-3 show hoop strain as functions of cyclic pressure and cycle number for one of the corroded fatigue test samples (i.e. the E-glass system that achieved 259,537 cycles to failure), respectively. Of particular note in Figure 4-3 is the change in strain range and maximum strain that occur as functions of cycle number. As observed, the maximum strain increases with increasing cycle number, while the strain range remains relatively constant over the period of measurement, which for this case was almost 100,000 cycles. The tests associated with this particular effort are critically important for evaluating the long-term performance of the composite repair.

To convert the above pressure cycle fatigue failure data into a meaningful design condition, it is recommended that the experimental data be divided by a value between 10 and 20. For the system having minimum performance (i.e. 19,411 cycles to failure), the design fatigue life at 36% SMYS ranges between 1,000 and 2,000 cycles (i.e. approximately 20,000 cycles to failure divided by 10 or 20), while for the maximum fatigue life (i.e. 767,816 cycles to failure) the design fatigue life is between approximately 38,000 and 76,000 cycles. In terms of applying these results to an actual pipeline, once the number of annual pressure cycles is obtained for a given system the calculation is relatively simple. For example, if a liquid pipeline experienced 2,000 annual cycles at a pressure range of 36% SMYS, the design life for the samples with the 38,000 design cycles is 19 years.

4.1.2 Composite Reinforcement (Inter-layer Strain Distribution)

When designing a composite repair system for long-term service, it is essential that the magnitude of stresses in the composite material not exceed a designated long-term design stress. ASME PCC-2 provides a means for determining the long-term design stress, recognized as s_{lt}, using test results for pipe samples pressurized from either 1,000-hour or 10,000-hour. Once the long-term design stress for a particular composite repair material has been established, it is important to actually measure stresses in the composite subjected to operating and yield pressures.

This section provides the reader with data acquired for two different composite repair systems. Strain gages were installed within the composite repair system (i.e. on layers as they were installed around the pipe) to measure strains within the repair, known as *inter-layer strain measurements*. This approach minimizes the uncertainty associated with trying to determine actual stresses in the composite material during pressurization of the pipe. For composite materials, and purposes of this discussion, stress is the product of strain and elastic modulus for the composite. It is necessary to measure, via mechanical testing, the elastic modulus in order for this calculation to be made. It is the author's opinion that testing to measure inter-layer strains is recommended to ensure that composite materials are not overstressed when subjected to design and hydrotest pressures. Without these measurements there is no assurance that repair materials are not overstressed, as overstressing could lead to failure of the composite material. Equally important, when composite reinforcement materials are overstressed their ability to provide the required reinforcement to damaged sections of pipe is reduced; this is especially true when considering long-term performance.[6]

Tests were conducted on two different composite repair systems, both of which used E-glass fibers. The objectives in testing were two-fold. The first was to determine the actual distribution of strain in the layers of the composite reinforcement; specifically, determining which layers carried the greatest percentage of the load. The second objective was to measure the maximum strain in the composite material for comparison to the ASME PCC-2 long-term design stresses, which were determined by 1,000-hour testing for both of the tested systems.

Figure 4-4 and Figure 4-5 plot hoop strain in the composite materials at 72% SMYS for Systems #1 and #2 as a function of radial position, respectively. Additionally, Figure 4-6 plots hoop stress as a function of internal pressure for System #2 using data collected during testing. Also included in this plot are average hoop strain data collected for the E-glass composite repair systems participating in the Pipeline Research Council International, Inc. (PRCI) MATR-3-4 long-term composite reinforcement study.

Table 4-1 presents a summary of data for both systems measured at 72% SMYS, along with a comparison of the measured stresses to the respective long-term design stresses. As a point of reference to the pressure cycle data previously discussed, System #1 achieved 140,164 cycles to failure, while Sample #2 was cycled 259,537 times before a failure occurred.

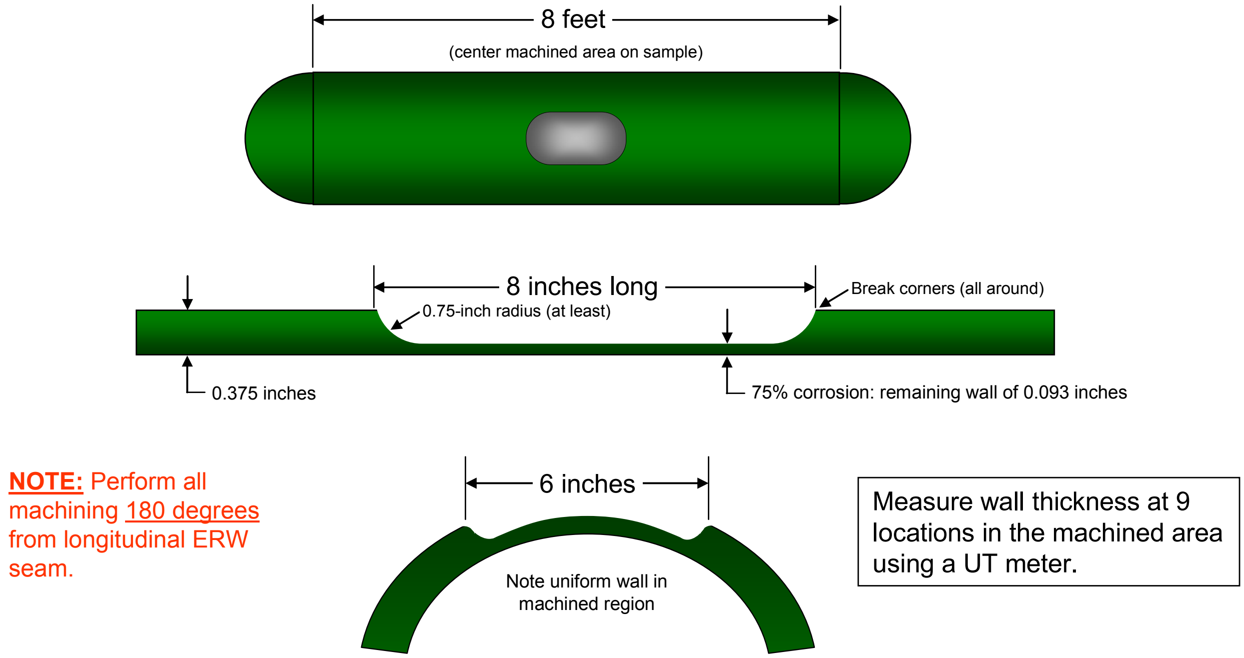
[6] The measurement of inter-layer strain using strain gages is not a requirement in ASME PCC-2. It is merely another means for quantifying performance. The stresses computed based on inter-layer strain measurements for all systems meeting the requirements of ASME PCC-2 have all been less than the ASME PCC-2-designated design stresses. Indirectly, the inter-layer strain testing has validated the technical validity in using ASME PCC-2 as a design standard.

Table 4-1: Comparison of Measured Stresses to PCC-2 Design Stresses

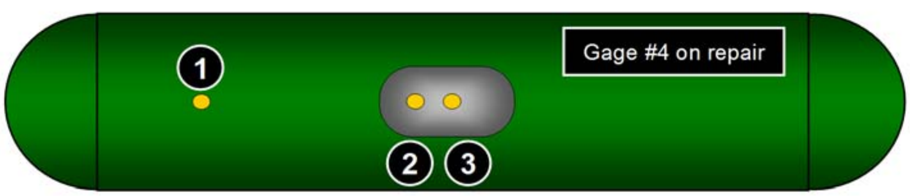
Stress Value	Calculation Variable	System #1 (t_{comp} = 0.76 inches)	System #2 (t_{comp} = 0.63 inches)
Mean Tensile Stress (based on short-term tensile testing)	A	51,700 psi	72,088 psi
Long-term Design Stress, S_{lt} (based on PCC-2 Appendix V testing)	B	20,369 psi	23,836 psi
Allowable Stress (based on short-term tensile testing)	C	10,184 psi	11,918 psi
Maximum stress in composite (based on measured strain values)	D	4,806 psi	9,438 psi
Maximum measured strain in steel (75% corroded region)		2,976 με	3,125 με
Resulting Design Margins			
Mean Tensile Stress vs. Allowable Stress (A/C)		5.1	6.0
Mean Tensile Stress vs. Maximum Stress (A/D)		10.8	7.6
Usage factor (percentage of allowable, D/C)		47%	79%

Note: 10,000 microstrain (με) equals 1 percent strain.

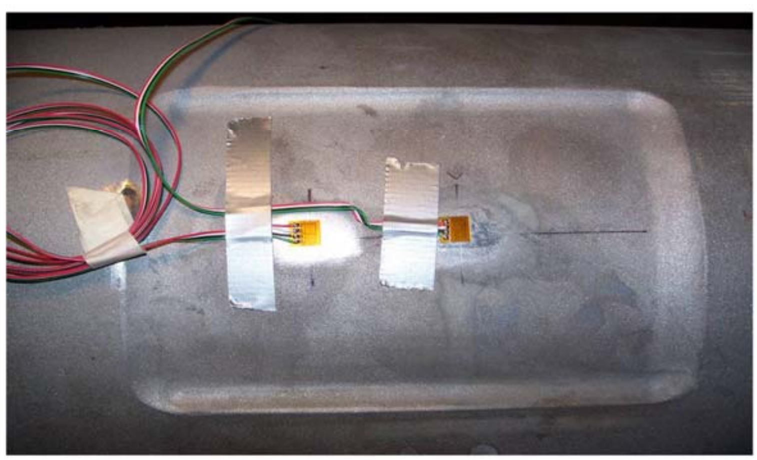
One of the most important observations made in reviewing the data presented in Table 4-1 is the relatively large design margins that exist for both systems, especially in relation to the short-term tensile strength. When comparing the measured stresses in System #1 and #2, the ratios of mean tensile strength to maximum stress for the composite materials are 10.8 and 7.6, respectively. If one considers the average stresses in the composite based on the strain gage results, as opposed to the maximum stress that is reported in Table 4-1, these ratios are even larger. The significance of these design margins should not be understated. In order for a composite material to provide long-term reinforcement, it is essential that stresses in the composite material and reinforced steel are kept to a minimum. As shown in Figure 4-6, hoop strains in the steel pipe beneath the System #2 repair were limited to approximately 0.3 percent when the test sample was pressurized to 72% SMYS.



Details on machining
(machined area is 8 inches long by 6 inches wide)



Location of strain gages installed on the test sample



Photograph of strain gages installed in the machined corrosion region

Figure 4-1: Layout for 75% corrosion in 12.75-inch x 0.375-inch, Grade X42 pipe

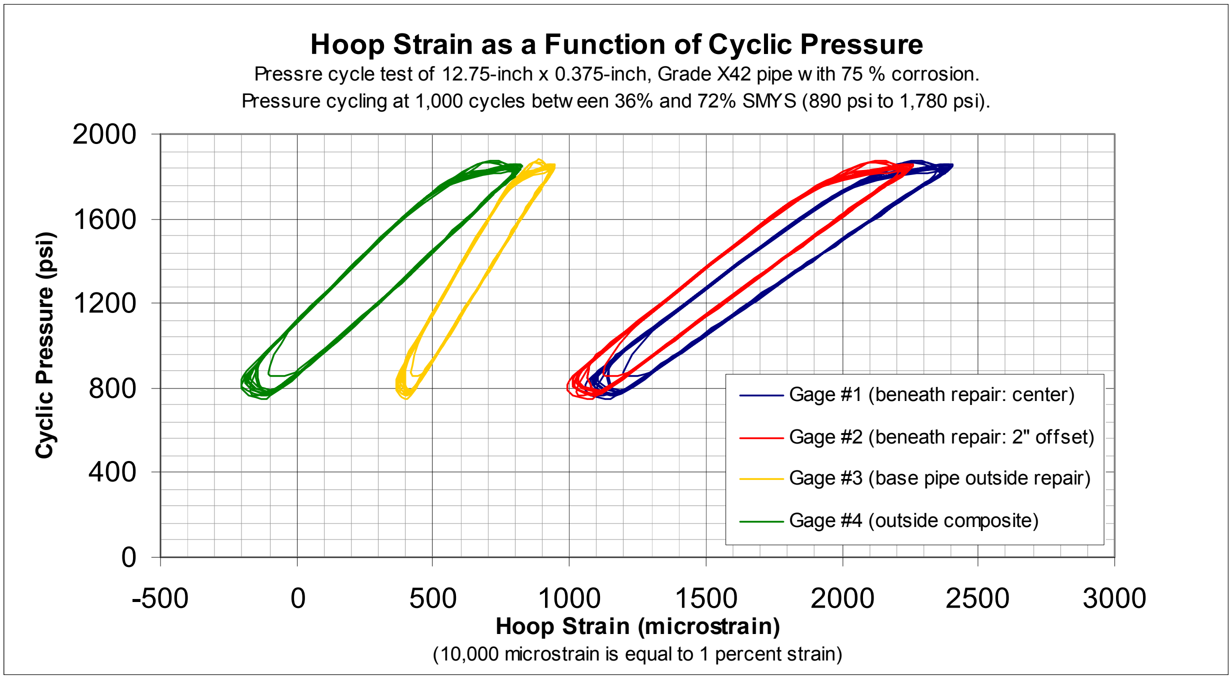


Figure 4-2: Hoop strain as a function of cyclic pressure for corroded sample

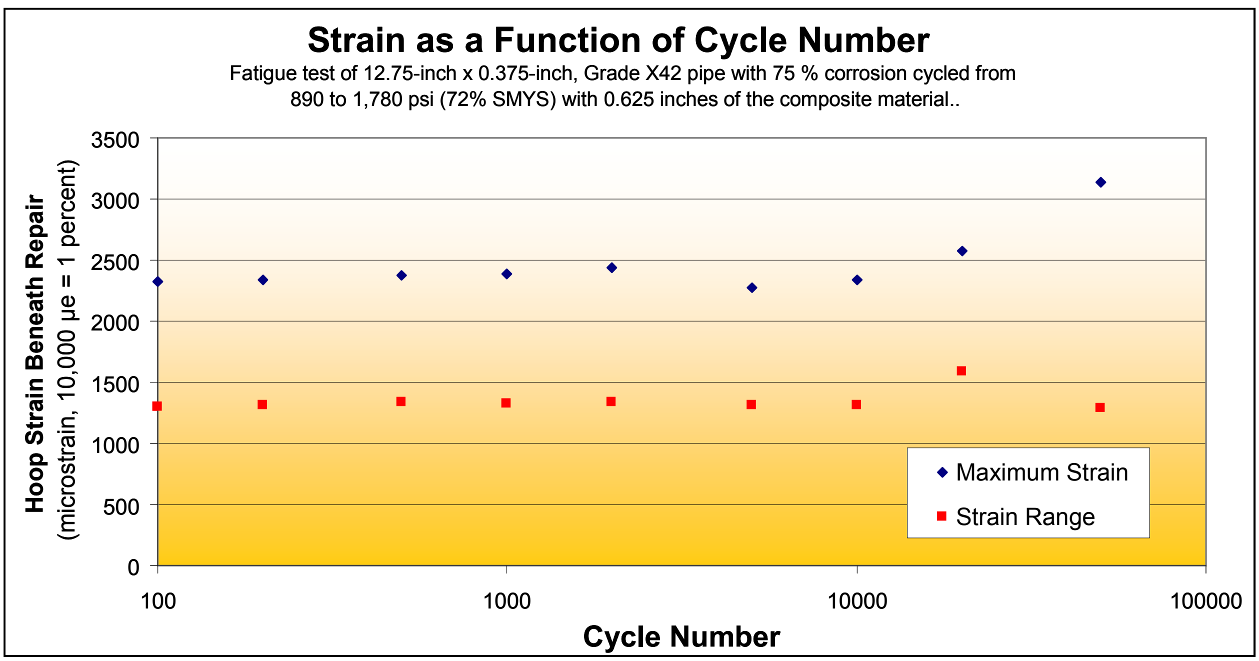


Figure 4-3: Hoop strain as a function of cycle number for corroded sample

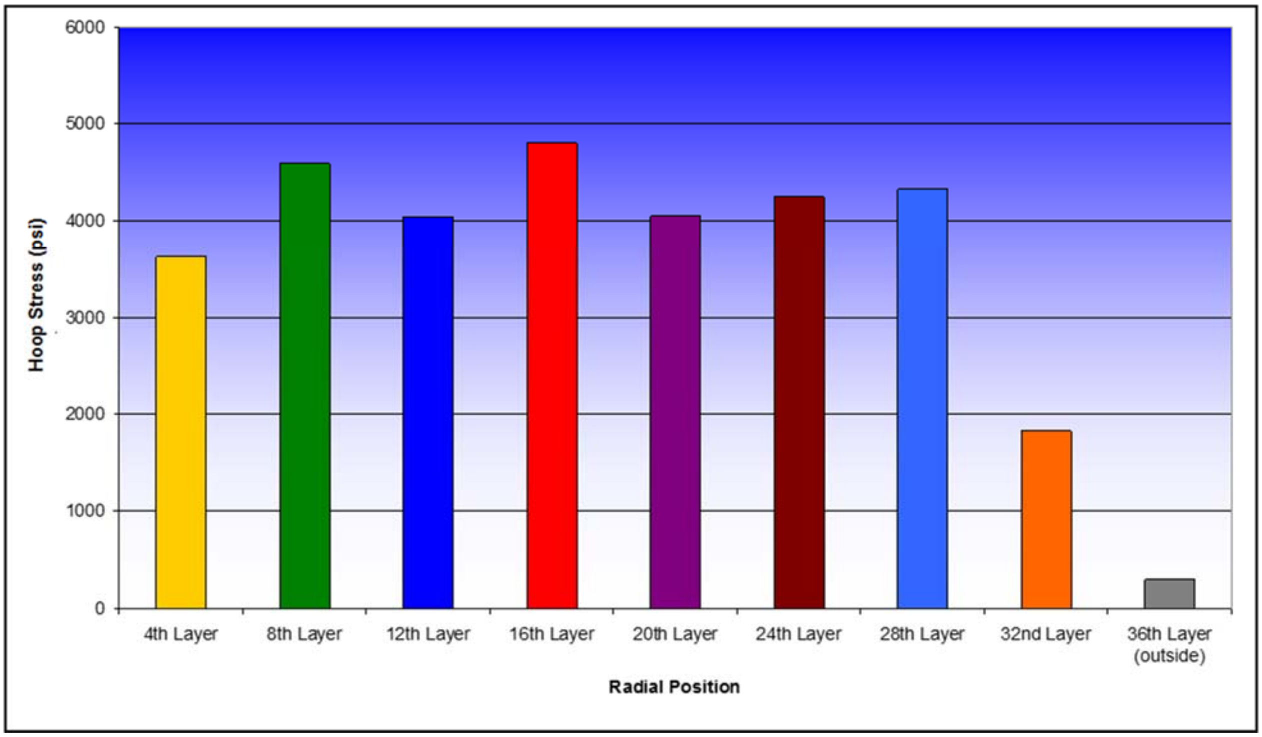


Figure 4-4: System #1 Hoop Strain at 72% SMYS (Function of Radial Position)
(Hoop stress calculated as the product of the measured strain and the composite's elastic modulus)

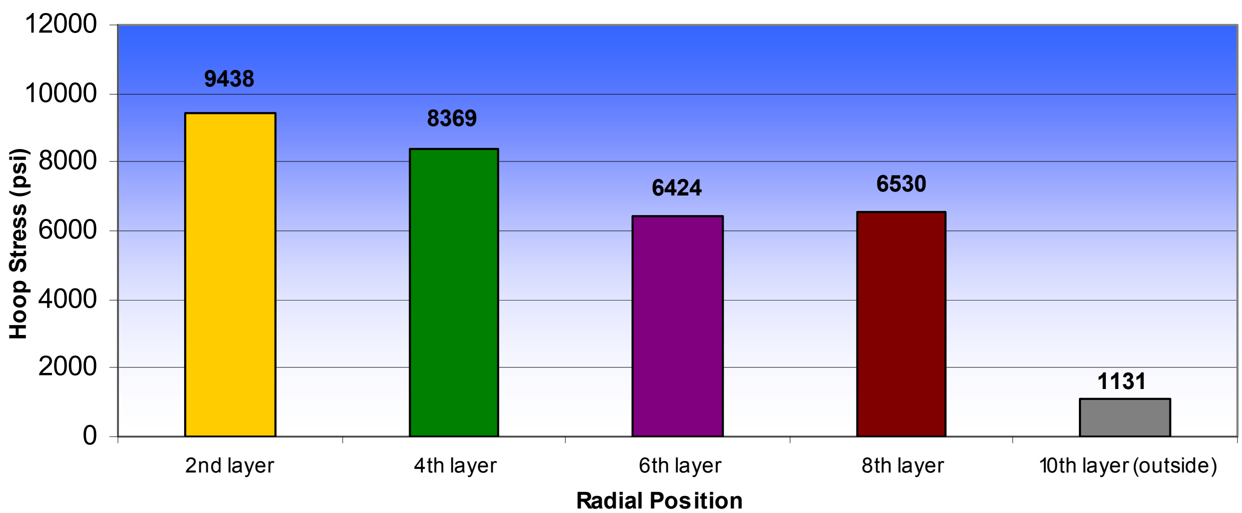


Figure 4-5: System #1 Hoop Strain at 72% SMYS (Function of Radial Position)
(Hoop stress calculated as the product of the measured strain and the composite's elastic modulus)

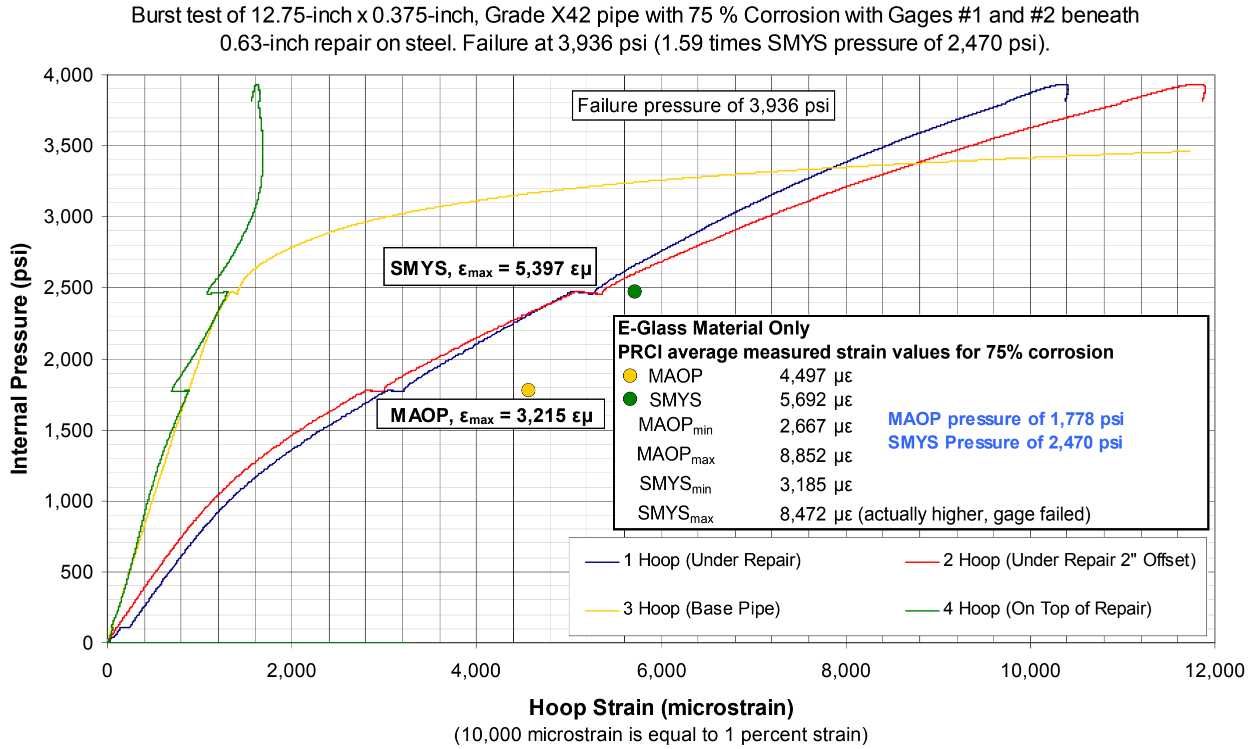


Figure 4-6: Measurement of strain in 75% corroded region for System #2

4.2 Repair of Dents

It is recognized that the vast majority of composite repairs are used to repair corrosion; however, the repair of dents is also common place. This section has been prepared to provide guidance on how to properly repair dents using composite materials. Also included are results from the PRCI MATR-3-5 study evaluating the repair of dents subjected to cyclic pressure service [13]. This study assessed the performance of plain dents, dents in girth welds, and dents in longitudinal ERW seams. The results demonstrated that when properly designed and installed, composite materials can reinforce dents to the point where they are no longer a threat to the integrity of the pipeline. As a case in point, one of the systems achieved 358,470 cycles at a pressure range of 72% SMYS before a leak developed in the ERW seam of the pipe. The conclusion is that this particular repair system was able to increase the integrity of the damaged pipe to be at least as good as the undamaged ERW seam.

For purposes of this discussion, dents represent local damage in the form of curvature changes, while mechanical damage involves dents combined with material loss in the form of a gouge or scratch. It is recognized that mechanical damage is a leading cause of pipeline failures. What makes mechanical damage so severe is the formation of cracks, specifically micro-cracking, which develops at the base of the gouge in the highly stressed region of the dent. During pressurization the elevated stresses at the crack tip propagate the crack to the point where failure occurs during a single cycle or over a period of time due to cyclic pressure loading. When composite materials are used to repair mechanical damage, it is essential that any form of cracking be removed by grinding. Experimental work has demonstrated that, in general, composite materials lack adequate reinforcement to ensure that cracks do not propagate when the repaired pipes are pressurized [14]. On the other hand, experimental investigations have shown that when gouges are removed by grinding, composite materials reduce stresses in the dented region and significantly increase the fatigue life over unrepaired mechanical damage.

Provided in Appendix E is a copy of the paper, *Repair of Dents Subjected to Cyclic Pressure Service Using Composite Materials*, from the Proceedings of 2010 International Pipeline Conference in Calgary (Paper No. IPC2010-31524) [13]. This paper provides details on this research program and how composite materials can reinforce dents by reducing strain both in terms of mean stress, as well as reducing the effects of cyclic pressure. One of the important observations made in this particular research program is that not all composite repair systems perform equally. Several systems were able to achieve the targeted 250,000-cycle run-out condition; however, two systems did not achieve average cycles to failure much greater than 40,000 cycles. This observation regarding composite performance supports the previous statement that composite manufacturers must be able to demonstrate the worthiness of their system in repairing pipelines by performance testing.

The following sequence of steps is recommended for repairing pipeline dent defects:

1. If applicable, remove the gouge by grinding with a hand-held power grinder. To ensure that the crack has been completely removed, as a minimum, magnetic particle inspection is recommended. The final step when grinding should be the use of a fine abrasive well to smooth all grind marks to ensure that no additional stress risers are present. Measure the remaining wall thickness using a UT (ultrasonic) meter. The depth of the grinding should not exceed 40% of the pipe's nominal wall thickness.
2. Prepare surface of pipe by sandblasting to near white metal (NACE Level 2 or SSPC 10).
3. Fill in dented region of the pipe with a filler material to ensure proper load transfer from the carrier pipe to the composite material.
4. Install the composite material using the appropriate number of wraps. This stage is critically important to ensure that adequate reinforcement is provided by the composite material. Only those systems

that have demonstrated their ability to reinforce dents using composite materials should be installed on the pipeline and manufacturers must produce documentation to demonstrate their capabilities and qualifications.

5. Allow the repair to cure in accordance with the manufacturer's recommendations.

4.3 Repair and Reinforcement Advanced Concepts

As industry developed confidence in using composite materials to repair corrosion and dents, it was to be expected that their use would expand to address other pipeline anomalies and features. Over the past five years several studies have been conducted by PRCI, pipeline operators, and composite manufacturers to evaluate the ability of composite materials to reinforce features such as the following:

- Wrinkle bends
- Welded branch connections
- Hard spots[7]
- Girth welds

The purpose of this section of the report is not to provide an exhaustive discussion on repairing and reinforcing pipelines, but rather provide Dominion with a method for how to address the repair of atypical features using composite materials based on the methodology embodied in the Engineering-Based Integrity Management Program (specifically the Level IV process).

4.3.1 Reinforcement of Wrinkle Bends

It is recognized throughout the transmission pipeline industry that failures in wrinkle bends have occurred. While identifying the causes and contributors to wrinkle bend failures have been the subjects of several studies, in 2010 six full-scale tests were conducted to evaluate the performance of wrinkle bends, including the assessment of composite materials (3 sets with each set having one reinforced and one unreinforced wrinkle). Figure 4-7 and Figure 4-8 are photographs showing the test set-up and composite installation, respectively.

Of the three sets of tests that were performed, results are presented for one set of wrinkle bends fabricated from 26-inch x 0.313-inch, Grade X52 pipe material. The test effort included the installation of strain gages near the wrinkle bends to monitor strain during testing. Internal pressure was held constant,

[7] A 20% solution of ammonium persulfate can be used as a test for identifying hard spots as outlined in ASME B31.8.

while axial tension loads were increased until failure occurred in the pipe material or a plastic collapse condition was observed via the strain gage readings (i.e., unbounded displacements with minimum increases in loading). Prior to testing, wrinkle geometries were measured using an optical mapping tool. One of the test samples was reinforced using Armor Plate® Pipe Wrap, while the other sample was tested without reinforcement. Of particular note in this study was corrosion that was present near the wrinkle bends. Although difficult to measure due to the presence of the wrinkles, pitting on the order of 30% of the pipe's nominal wall was detected in both the unreinforced and reinforced test samples. The wrinkle bend severity ratios, h/L, were measured to be 0.123 and 0.137 for the unreinforced and reinforced samples, respectively.

During the test, an internal pressure of 900 psi was applied to the sample and held constant while an axial tension load was applied to the samples. The unrepaired sample failed by leaking at a combined load of 1,527 kips, while the repaired sample failed by rupture at a combined load of 1,815 kips. The unrepaired sample developed a leak in the corroded region near a wrinkle.

Figure 4-9 plots axial strain as a function of axial tension loading. Provided below are several noteworthy observations made in reviewing the plotted data.

- At an axial stress of 36% SMYS (455 kips), the following strains were measured (where 10,000 microstrain, με, equals 1% strain):
  - Base pipe without wrinkle bend (calculated): 593 με
  - Unreinforced wrinkle bend (h/L = 0.123): -3,508 με
  - Reinforced wrinkle bend (h/L = 0.137): -1,611 με
- While the reduction in strain provided by the composite material is critically important, it should also be noted that the composite material increased the ultimate load capacity of the pipe having wrinkle bends. Corrosion pitting in both samples was on the order of 30%, yet the composite-reinforced sample increased the axial tensile capacity to achieve a stress level in the base pipe on the order 71 ksi (i.e. 1,815 kips / [π· 26 inches x 0.313 inches]). This stress level is in excess of the minimum tensile strength of the Grade X52 pipe material (i.e. 66 ksi).
- Because the fractures that typically develop in wrinkle bends are circumferentially-oriented, any composite reinforcement must be able to provide significant levels of axial reinforcement. The Armor Plate® Pipe Wrap system uses E-glass material with a tensile strength and elastic modulus of 72 ksi and 4.4 Msi. To be effective, 50% of the composite fiber material was oriented in the axial direction.

The reasons for the success of this particular system, as demonstrated in this particular test program, are the relatively high strength and stiffness values of the composite material.

- The length of the composite repair is extremely important. As part of the composite design, calculations should be made to ensure that the calculated product of the repair area (π x *pipe diameter* x *repair length*) and the adhesives' lap shear strength are sufficient. Any repair where axial reinforcement is required should consider this issue, including the reinforcement of wrinkle bends and girth welds.

Figure 4-7: Photographs showing testing set-up for wrinkle bend testing

Figure 4-8: Photographs of composite materials on wrinkle bend samples

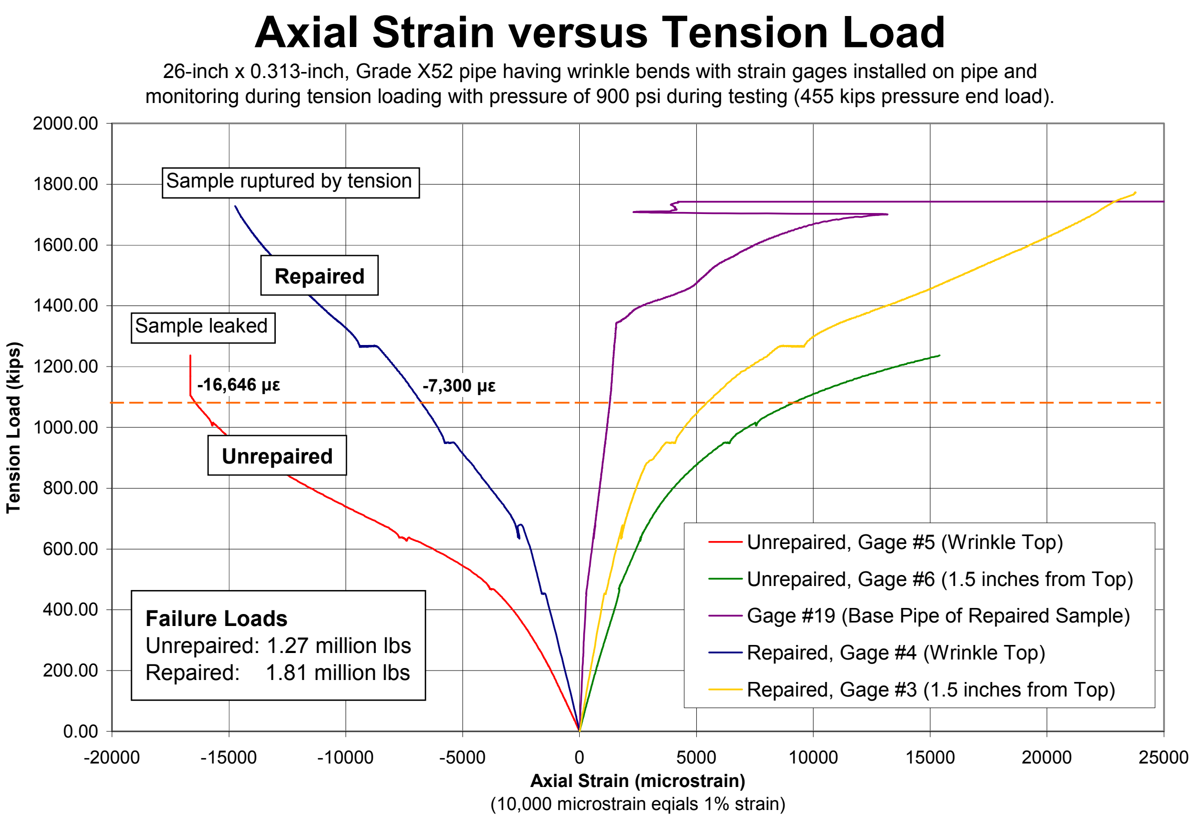


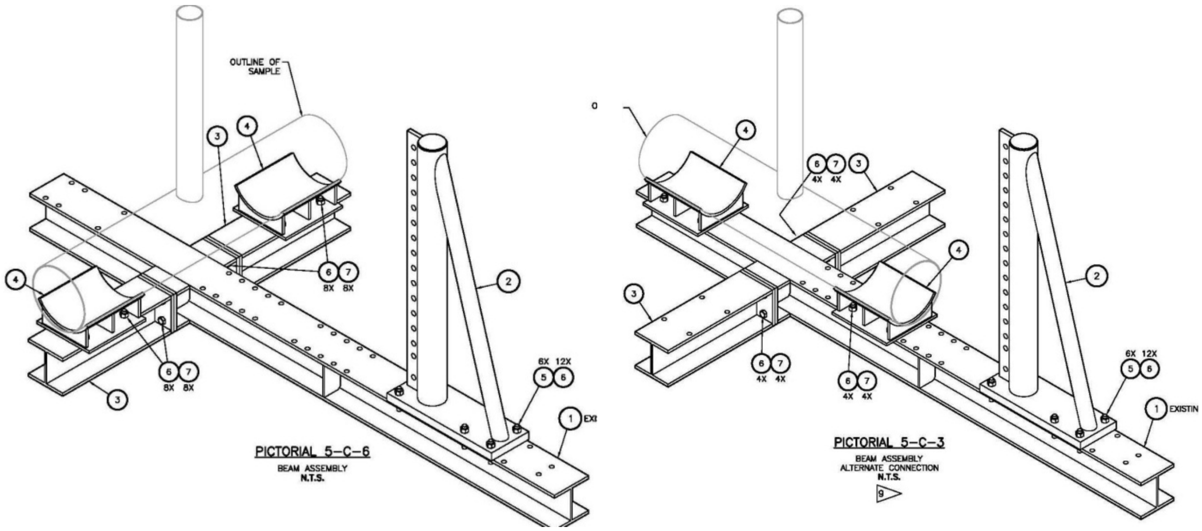
Figure 4-9: Axial tension versus strain for the wrinkle bend test samples

(*Tension Load* is the sum of tension load from the frame and the end load due to internal pressure)

4.3.2 Reinforcement of Welded Branch Connections

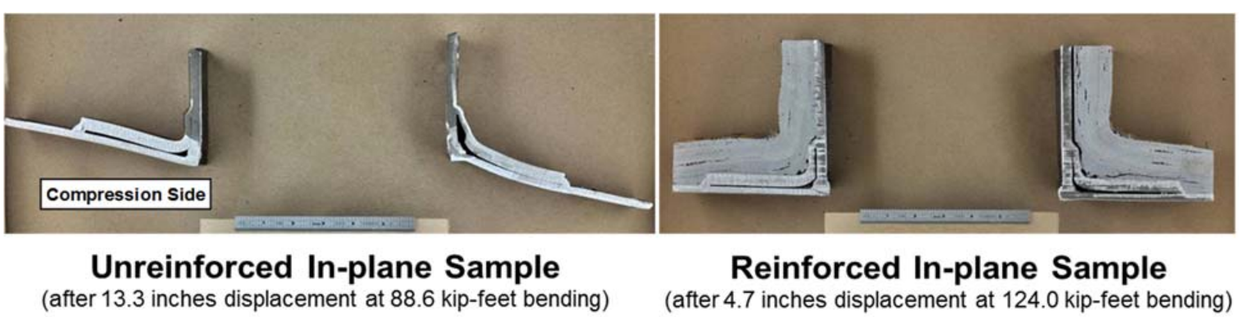
Welded branch connections are common in transmission pipelines. A study was conducted for a gas transmission pipeline operator to evaluate the ability of composite materials to reinforce branch connections. Of particular interest was the reinforcement of branch connections subjected to in-plane and out-of-plane bending loads. The study involved simulating the bending loads on branch connections in service. Bending loads were applied to the branch pipe in the plane of the run and branch pipe (i.e. in-plane), as well as out of the plane (i.e. out-of-plane). Samples were also tested to determine the effectiveness of the composite in strengthening the branch connections. The unreinforced sample referenced in this study used an under-reinforced saddle branch connection, while the reinforced sample corresponded to a composite reinforced saddle branch connection (i.e. composite material installed over the under-reinforced saddle branch connection). The run pipe materials included in this study were 24-inch x 0.250-inch, Grade X70 pipes and the branch pipes were 8.625-inch x 0.322-inch, Grade X52 pipes. A total of four samples were tested. Figure 4-10 provides drawings and photographs providing further details on this particular study.

The conclusion from this study was that when properly designed and installed, composite materials can reinforce branch connections subjected to internal pressure in conjunction with in-plane and out-of-plane loading. To ensure optimum performance, the reinforcement must have adequate stiffness, related primarily to elastic modulus and thickness of the composite material, as well as employ proper installation techniques.



Diagrams showing set-up for in-plane (left) and out-of-of-plane (right) bending tests

Final displacements for in-plane unreinforced (left) and reinforced (right) bending tests



Post-test sections showing results for the unreinforced and reinforced conditions

Figure 4-10: Diagrams and photographs for the branch connection tests

4.3.3 Reinforcement of Girth Welds

A PRCI-sponsored program, MATR-3-edevaluating the use of composite materials in reinforcing vintage girth welds. Participants in this study included the following composite repair companies:

- Air Logistics
- Armor Plate, Inc.
- Citadel
- Pipe Wrap, LLC
- Western Specialties

The program involved the reinforcement of 12.75-inch x 0.188-inch, Grade X42 pipe samples with defective girth welds that did not include a root pass (i.e., lack of penetration weld defects). Each manufacturer was responsible for repairing three pipe samples that included one pressure-tension sample, one pressure-tension sample with a reduced bonding area, and a pressure-tension-bending sample. Additionally, two unreinforced test samples were tested (i.e., pressure-tension and pressure-tension-bending) to provide a baseline data set to which results for the reinforced samples could be compared. Prior to conducting the destructive tension and bending tests, all reinforced samples were subjected to 18,000 pressure cycles ranging from 445 psi to 890 psi (36% SMYS to 72% SMYS). This condition approximates a 20-year service life for gas pipelines, assuming an aggressive pressure condition, that experience 889 cycles per year at a stress range of 36% SMYS. Also included for each test to failure was an internal pressure of 445 psi (36% SMYS) that was held constant during testing.

Figure 4-12 provides a representative cross-sectional view of the girth welds, including the lack of penetration on the inside surface of the pipe. The samples were basically fabricated by butting the two ends of the pipe together and installing a single pass weld on the outside. Figure 4-13 is a macrograph showing a section from one of the test samples. The lack of penetration is clearly visible. Figure 4-13 is a schematic diagram showing the position of the girth welds relative to the composite material and strain gages.

Although there were some differences in the bending capacities for the five pressure-tension-bending samples, all of the reinforced systems did well in the sense that the maximum level of distortion occurred outside of the reinforcement; validating that the reinforced sections of the pipe had greater stiffness than the base pipe itself. However, there were some differences in the results for the pressure-tension samples. Considering the reinforced pressure-tension samples with full bonding areas, tension to failure loads ranging from 433 to 522 kips. One system was able to provide sufficient reinforcement to generate a failure occurring in the base pipe near a welded bosset away from the repair.

This program has not specifically addressed long-term performance of the composite repair systems, although it is recognized that all but one of the composite manufacturers participated in the PRCI MATR-3-4 study to address the long-term durability performance of their systems. Composite materials are widely-recognized as a means for reinforcing damaged pipelines. Programs such as this girth weld study are valuable for quantifying the level of performance that can be expected from the current available composite repair technology.

The results of this program demonstrate that when properly-designed and installed, composite materials reduce strain in girth welds and increase the limit state capacities considering combinations of pressure, tension, and bending loads; thus, providing operators a repair method that adequately restores the integrity of pipelines with defective girth welds. Additionally, the Western Specialties, LLC system was able to reinforce a defective girth weld so that failures in tension and bending occurred outside of the reinforced region.

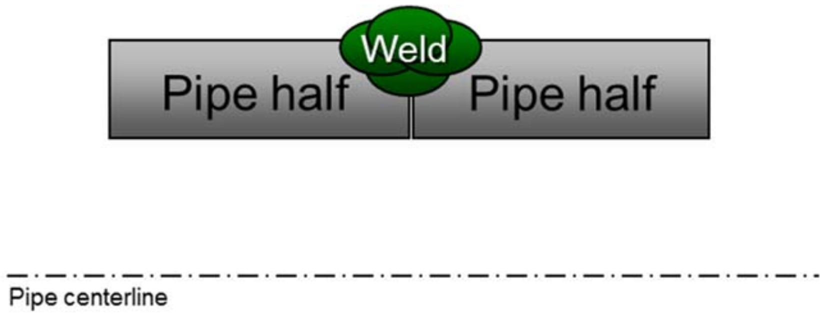


Figure 4-11: Schematic showing girth weld installation and defect.

Figure 4-12: Metallographic section of the defective girth weld material

Note the discontinuity—a lack of fusion on the ID surface (seen at bottom of photomicrograph).

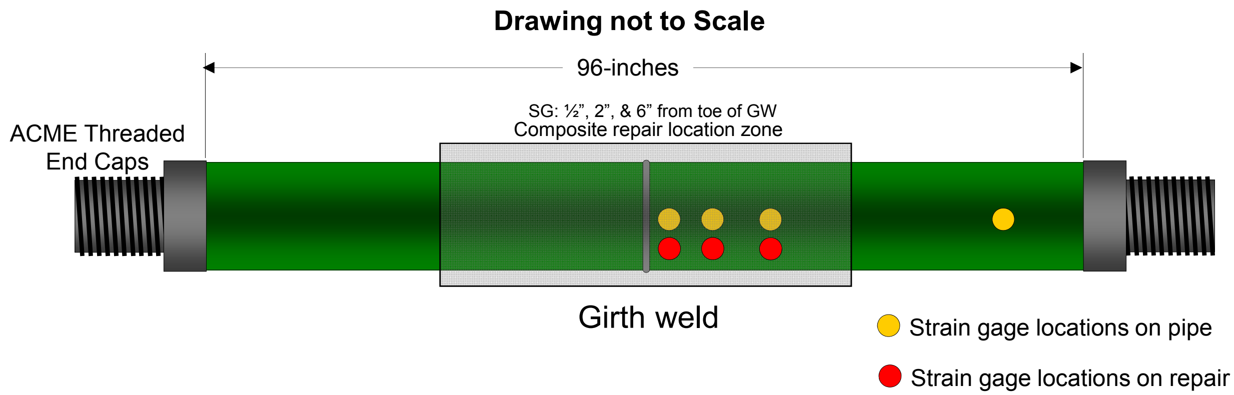


Figure 4-13: Strain gage installation map for tension to failure samples.

4.3.4 Reinforcement of Planar Defects

A study was conducted to investigate the reinforcement of LF-ERW (low frequency electric resistance weld) flaws located in a 16-inch x 0.312-inch, Grade X52 ethylene pipeline.[8] The study was prompted by an in-service leak that was discovered in an LF-ERW seam during routine maintenance activities. The investigation was subsequently expanded as a result of the discovery of several additional leaks. An initial failure analysis of the leak location was conducted followed by broader material testing, full-scale testing, and metallurgical analysis of the remaining pipe. The use of composite repair systems as a feasible method of LF-ERW seam reinforcement was also examined. As part of this study, in addition to the 16-inch NPS samples (cf. Figure 4-14) testing was also conducted on 8.625-inch x 0.250-inch. (219-mm x 6.35-mm) pipe material having LF-ERW seams. Results of this study are reported in a paper by Alexander et al presented at the 2016 International Pipeline Conference (*Repair of Planar Defects in Low-Frequency ERW Long Seams Using Composite Reinforcing Materials*, Paper No. IPC2016-64082). A copy of this paper is provided in Appendix F.

EDM (electric discharge machining) notches were installed in the ERW bond line, as shown in Figure 4-15. Test results documented the potential for composite repair systems to provide reinforcement to LF-ERW flaws and crack-like defects. Distinct contrasts were observed between the performance of samples with unreinforced and reinforced notches subjected to cyclic pressure and burst tests. Reinforced samples exhibited improvements in pressure cycle life and significantly increased burst pressure capacities as compared to unreinforced samples. As shown in Figure 4-16, the composite reinforcement system was

[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.

able to provide reinforcement in reviewing so that no crack growth was observed in the EDM notch even after burst testing. What is also important in reviewing the images in this photo is the precision achieved when the EDM notches were installed in the ERW bond line.

The results of this program demonstrate that, when properly designed and installed, composite materials are an effective means for reinforcing LF-ERW long seam weld flaws and other planar defects. The composite repairs served to ensure that cracks neither form nor propagate during aggressive pressure cycling and burst testing.

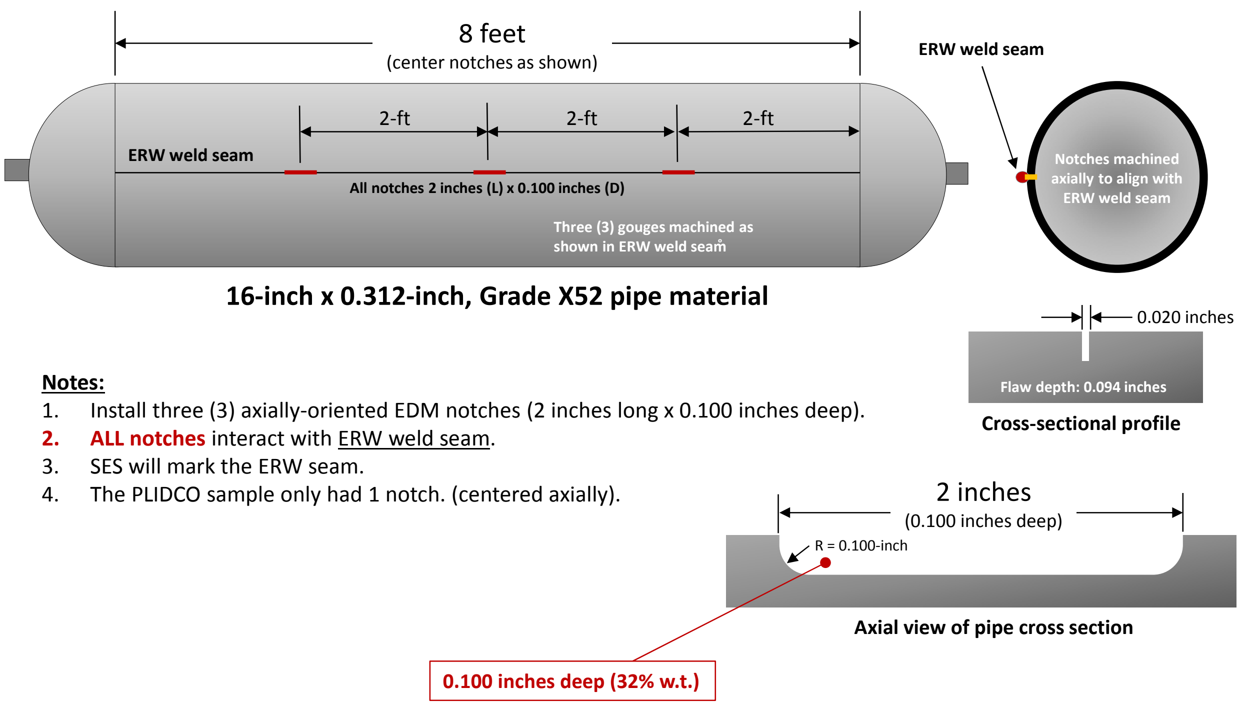


Figure 4-14: Schematic of 16-inch Pipe Samples with EDM Notches

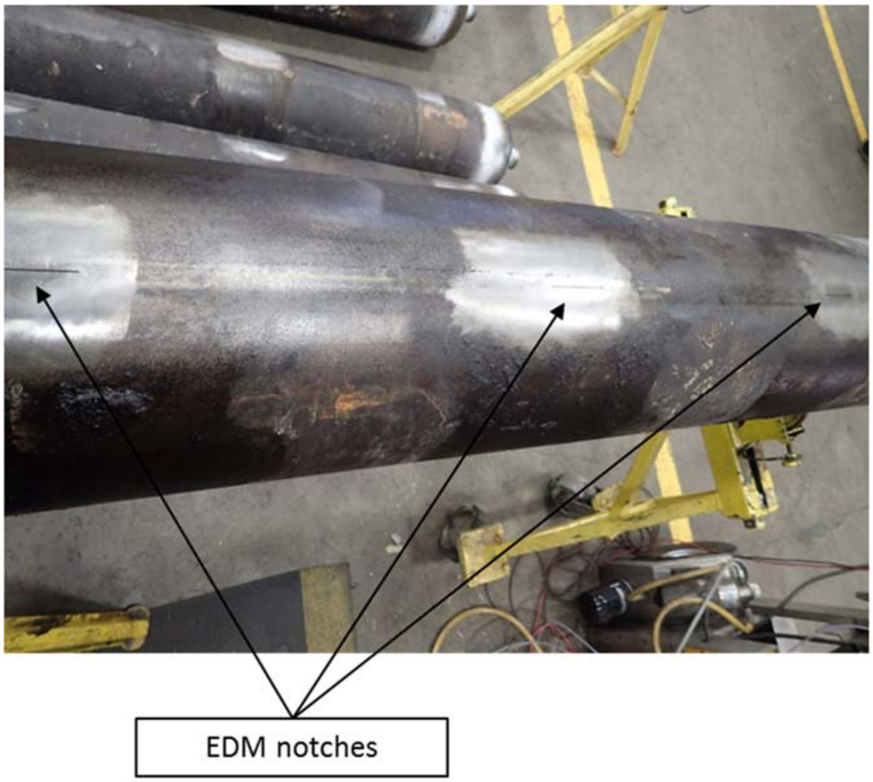


Figure 4-15: Photograph of EDM notches

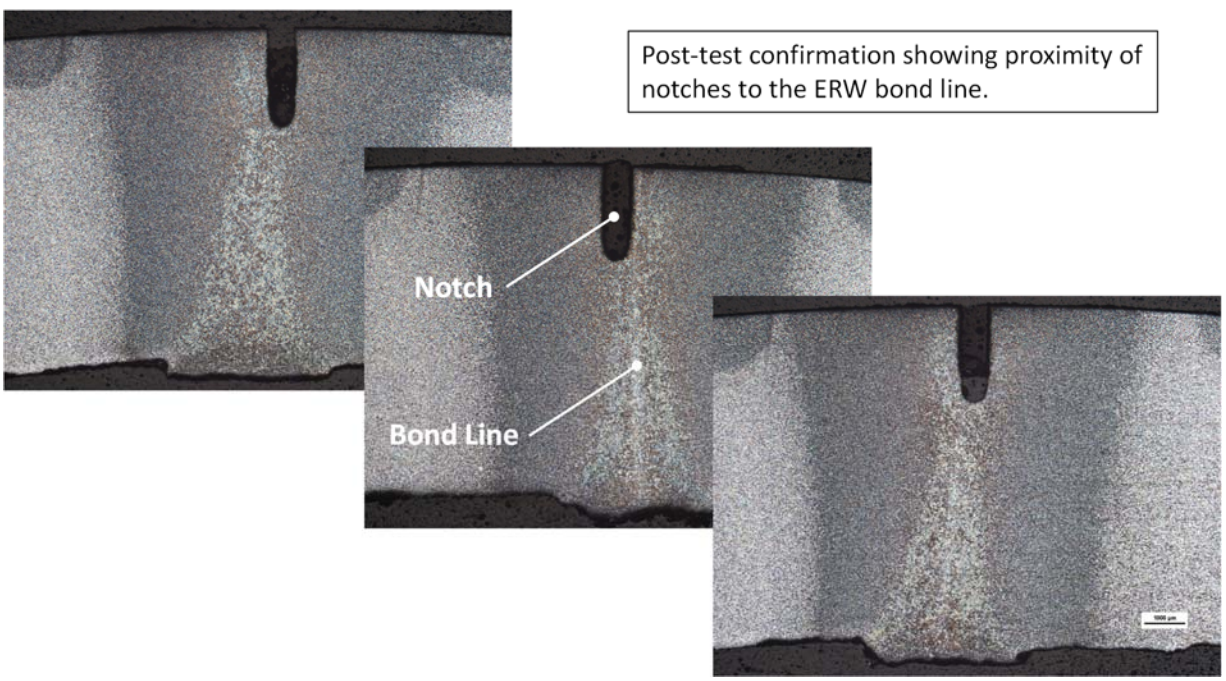


Figure 4-16: Sections of EDM notches through ERW Bond Lines

5.0 RISK ANALYSIS

Performing a risk assessment is an effective means for ensuring that composite repair systems are adequately designed and installed in a manner that will meet the applicable service requirements. There are two phases of work associated with the risk assessment. The first involves conducting the risk assessment using the prescriptive elements identified in ASME PCC-2, Part 4 Nonmetallic and Bonded Repairs, Section 1.3 *Risk Assessment* that set the foundation for a comprehensive risk assessment. The second phase of work integrates the elements associated with a Failure Modes and Effects Analysis (FMEA) where numerical weighting values are applied to risk factors that include probabilities of occurrence, severity, and detection.

It should be noted that not all composite repairs will require a detailed risk analysis; however, there are conditions where additional efforts are warranted. The combination of the PCC-2 risk assessment elements and the FMEA provide pipeline operators with a comprehensive means for maximizing the likelihood that the composite repair will be properly designed, installed, and function as intended to meet the required service conditions. The sections that follow provide details on these two phases of work.

5.1 Details of the Risk Analysis

As more sophisticated methods are being employed by pipeline operators in managing integrity, performing risk analyses has become an important part of the process. The use of composite materials has become an important part of many company's integrity management programs, so a discussion on conducting a proper risk analysis is warranted. Guidelines are provided in Paragraph 1.3 of Article 4.1 of ASME PCC-2 for performing a risk analysis on a composite repair. Provided below is the text from this document.

> An assessment of the risks associated with the defect and repair method shall be completed in line with the relevant industry best practice. When applying a Repair System in accordance with this Article the following items shall be considered:
>
> (a) assessment of the nature and location of the defects
> (b) design and operating conditions for the pipe and contents (including pressure, temperature, sizes, and combinations thereof)
> (c) repair life (see paragraph 1.4)
> (d) geometry of the pipe being repaired

(e) hazards associated with system service

(f) the availability of the personnel with the necessary skills

(g) the ease with which it is practicable to execute surface preparation operations

(h) performance under upset and major incident situations including impact, abrasion, fire, explosion, collision, and environmental loading

(i) failure modes

(j) inspectability

(k) the Repair System materials

The information and data describing any hazards shall be included in the method statement (paragraph 4.4) to be used on site.

The application of these Repair Systems will typically change the mode of failure from rupture to a leak; the consequences of failure will therefore be reduced. A repair applied in accordance with this Article will also reduce the probability of failure.

As noted in (c) above, Paragraph 1.4 is referenced; the associated text is provided below.

The repair life is the useful service period of the Repair System, as defined by the design assessment. This may be limited by the defect type and service conditions (e.g., internal corrosion). The repair life will depend on the Repair System.

Also referenced in Paragraph 1.3 is Paragraph 4.4, *Method Statements*. Listed below are the tasks covered by this particular method statements.

- ¶ 4.4.1 Health and Safety
- ¶ 4.4.2 Repair Design
- ¶ 4.4.3 Repair Application
- ¶ 4.4.4 Quality Assurance
- ¶ 4.4.5 Environmental

The intent in conducting a risk analysis based on the guidelines provided in ASME PCC-2 is to provide operators with pertinent information related to each item to ensure that an optimum repair solution is developed. For those areas where a greater perceived risk is identified, measures should be taken to either minimize this risk, or eliminate it altogether.

5.2 Failure Modes and Effects Analysis

An extension of the risk analysis effort involves the execution of a Failure Modes and Effects Analysis (FMEA). An in-depth discussion on performing an FMEA is outside the scope of this document; however, provided a formal definition of FMEA is provided as follow.

> A failure modes and effects analysis (FMEA) is a procedure in product development and operations management for analysis of potential failure modes within a system for classification by the severity and likelihood of the failures. A successful FMEA activity helps a team to identify potential failure modes based on past experience with similar products or processes, enabling the team to design those failures out of the system with the minimum of effort and resource expenditure, thereby reducing development time and costs. It is widely used in manufacturing industries in various phases of the product life cycle and is now increasingly finding use in the service industry. Failure modes are any errors or defects in a process, design, or item, especially those that affect the customer, and can be potential or actual. Effects analysis refers to studying the consequences of those failures.[9]

By conducting an FMEA, a user of composite repair materials is in a position to actually quantify the risk associated with a given installation. Quantifying risk is achieved by assigning to each identified risk a numerical value associated with the occurrence, severity, and likelihood of detection. The product of these three numbers is known as the Risk Priority Number (RPN). Provided in Table 5-1 is a *Failure Modes and Effects Analysis* Worksheet that includes the factors of interest and their associated risk factors. Provided in this document is a list of RPNs based on an assessment conducted previously for an operator in evaluating the repair of a given corrosion defect in a process piping facility. The following FMEA risk ranking was determined as presented by the data in Table 5-1. Included in the following list are the calculated RPN values; the product of the Occurrence, Severity, and Detection values: (RPN = O x S x D).

- Adhesive bond failure RPN = 360
- Insufficient number of axial fibers RPN = 200
- Composite degradation due to high temperatures RPN = 108
- Outer layer degradation RPN = 60
- Composite material thickness insufficient RPN = 54

[9] Information obtained from http://en.wikipedia.org/wiki/Failure_mode_and_effects_analysis

As seen in the preceding list, the adhesive bond failure is the primary concern for this particular installation. As a result, the operator was encouraged to take all steps necessary and reasonable to achieve the best bond possible. This example provides a clear demonstration in how operators and composite manufacturers can work together to minimize risk by determining the steps required to design and install an optimized composite repair system. The benefit in conducting the FMEA is that the Risk Priority Numbers help determine the order of focus and concern, thus reducing the likelihood that a subjective-based decision might result.

Table 5-1: Failure Modes and Effects Analysis Worksheet

Potential Failure Mode	Potential Effects of Failure	Potential Cause(s)	O (occurrence rating)	S (severity rating)	D (detection rating)	RPN (risk priority number)	Recommended Actions
Adhesive bond failure	Failure to provide axial reinforcement	Poor surface preparation / Uncured adhesive	5	9	8	360	After ensuring that a sufficient amount of composite material has been installed based on the designated corrosion level, this is the most important facet of the repair. Keys to success are good surface preparation and ensuring the adhesive has cured. The key is to ensure that corrosion does NOT develop beneath the repair.
Composite material thickness insufficient	Potential for burst failure	Incorrect calculations and/or poor installation	3	9	2	54	This is rarely an issue as most manufacturers have calculators that determine the required composite thickness. However, post-installation inspection is critical.
Outer layer degradation	Chalky outer surface, moisture ingression	Insufficient or absent external coating	5	6	2	60	Most manufacturers recommend that the outer surface be coated or painted if the pipe is to be exposed to UV. This is even more important offshore.
Insufficient number of axial fibers	Insufficient axial reinforcement	Poor design	5	5	8	200	Because most repairs focus on "hoop" reinforcement, axial reinforcement is often neglected. The operator should ensure that adequate axial reinforcement is present.
Composite degradation due to high temperatures	Loss of reinforcement	Improper material selection, operating beyond resin capacity	3	9	4	108	Operators should insist that manufacturers provide material strength data as a function of temperature. Idealistically, it would be good to see full-scale test data at elevated temperatures.

6.0 DISCUSSION

In addition to the previous discussions on using composite repair materials, there are several additional items that should be discussed. These include notes of caution with regards to potential failure modes, inspection of repairs, and documentation and record keeping.

6.1 Notes of Caution on Potential Failure Modes

Experience has shown that there at least are three common reasons that a composite repair system could fail to perform as designed. Care should be taken to ensure that none of these conditions occur.

- Using products that exceed the recommended shelf life or published expiration date. The concern is that products will fail to set-up (i.e. cure) before the pipeline is placed back in service. Two-part epoxies have a shelf life; all such products that are provided without a “use by” date should not be used. Similarly, any epoxy products that have exceeded the *use by* date should not be used.
- Not providing adequate time to obtain full cure, failing to adequately protect the surface of the pipe, or failing to prevent unacceptable levels of moisture ingression into the repair system before curing. The concern is that if excessive levels of moisture enter into the composite repair before it cures, maximum strength of the composite might not be achieved. Several manufacturers use a plastic shrink wrap material around the composite that is typically removed after the repair has been allowed to cure. If any concerns exist in relation to the potential for moisture ingression before proper curing has taken place, use of plastic shrink wrap material is recommended. For those composite repair systems that require off-gassing such as water-activated urethanes, the plastic shrink wrap should be perforated to permit proper curing of the resin.
- Insufficient amount of composite material is installed. This is only a potential issue for wet wrap systems, as opposed to rigid coil systems that have the same number of layers for all repairs. Care should be taken to ensure that the proper composite thickness has been installed. It is also recommended that a measurement of pipe or fitting diameter be made before and after application of the repair. The two measurements could then be compared to verify the thickness.
- Historically, the pipeline industry has not been concerned with the installation of composite materials with internal pressure in the pipe. Several studies, including one funded by a pipeline operator and the PRCI MATR-3-11 study, have demonstrated that repaired corrosion defects with depths up to 50% of the pipe’s nominal wall thickness are not a concern when installations are made with internal

pressure. However, recent limited cyclic pressure fatigue testing on the reinforcement of plain dents with internal pressure has brought to light there might be need for concern; fatigue lives of reinforced plain dents were not significantly greater than those associated with unreinforced plain dents. It appears that the difference between the corrosion and the plain dent is the flexure that occurs in the dented region of the pipe sample, which does not take place to the same degree in reinforced corrosion features. For this reason, operators are encouraged to look carefully at this issue and ensure that for their particular cyclic pressure conditions this is not a concern.

- Cyclic pressure is present in all pipeline systems, although it is certainly more pronounced in liquid transmission pipeline systems than in gas transmission systems where cyclic pressure is typically not an issue. For this reason, operators are encouraged to evaluate their respective composite reinforcing technologies to ensure that the resulting fatigue lives of reinforced features, such as corrosion and plain dents, are acceptable. Based on industry's experience, the better performing composite technologies are able to achieve at least 150,000 cycles when used to reinforce a 75% corrosion defect in a 12.75-inch x 0.375-inch, Grade X42 pipe material cycled from 890 to 1,780 psi (i.e., 36% to 72% SMYS). According to TR-05-01 Report, *Evaluation of Natural Gas Pipeline Fatigue due to Internal Pressure Cycling*, the conclusion for gas pipelines I that "Fatigue due to internal pressure cycling is not a threat under existing operating conditions."
- The effects of elevated temperatures on the performance of composite repair technologies should not be discounted. A study was conducted by the Gas Technology Institute (December 2010) that evaluated the short and long-term adhesive lap shear strengths of seven commercially-available composite repair systems. The tests were performed by applying shear loads on the adhesives positioned between two layers of the composite at temperatures of 70°F, 105°F, and 140°F. The program demonstrated that the adhesive bond strength for all systems declined with increasing temperature; however, at least one system had an unacceptable level of degradation at elevated temperatures.
- A final comment is made regarding the types of features and defects that are to be reinforced. It is critically important that only "smooth" defects are reinforced; any sharp features such as kinks and excessively-sharp wrinkles are likely to be problematic for long-term service, especially in the presence of cyclic pressures. Smooth defects and features such as plain dent and wrinkle bends have been successfully repaired in the field, supported with empirically-generated test results.

6.2 Inspection of Repairs

Once installed, the composite repair must be visually inspected by a qualified company-designated inspector. This visual inspection is to ensure that the composite installation was performed in accordance with the composite repair procedures provided by the respective manufacturer.

In ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix 1, a two-page *Component Repair Data Sheet* is included that is an ideal resource for operators who want to ensure that all facets of the repair have been completed. A copy of this data sheet is included in Table 6-1 (also included in Appendix B). It is recommended that Dominion either use the ASME PCC-2 data sheet in its current form, or create a similar form, that includes company-specific items as appropriate. The goal is to ensure that all steps are completed and documented. It is essential that all steps recommended by the manufacturer be completed to ensure that the repair performs as designed.

There are currently several inspection technologies that possess the ability to identify disbondment and delamination within composite repairs; however, at the present time a clear correlation between the presence of disbondment and delamination defects and reduction in the composite system's performance is absent. Further, the technologies that have been evaluated appear unable to clearly identify exactly where disbondment and delamination defects are within the multi-layer repair (i.e., unable to distinguish if the imperfections are located on the 1st or 6th layer, as the case might be). At the present time the inspection technology appears to be more *qualitative* rather than *quantitative*. However, as with all technologies, advances in future capabilities will make the preceding statement obsolete.

6.3 Record Keeping

Recordkeeping is an important part of any composite repair. A *Component Repair Data Sheet* is provided in Table 6-1. This document is a modified version of the table included in ASME PCC-2-2015, Part 4 – Article 4.1, mandatory Appendix I. This data sheet should be used to capture and record the critical information associated with an anomaly prior to design of the composite repair solution. Provided in Table 6-2 is a checklist that can be used to verify that the composite repairs have been properly installed [11]. Where appropriate, notes should be taken to document exactly what was done in performing a particular repair, including any problems or untoward situations that occurred. With increased regulatory compliance issues, the important for sound documentation is critically important.

6.4 Unconventional Applications of Composite Reinforcement

One of the subjects addressed in this guideline is the reinforcement of what could be called "unconventional applications" of composite reinforcement. Historically, the largest application of composite wraps has been to reinforce corrosion anomalies, with a second being the reinforcement of plain dents. As has been presented, using advanced engineering methods that involve analysis and testing it is possible to apply composite materials to reinforce a wide range of pipeline features and anomalies that include elbows / bends, tees, wrinkle bends, girth welds, planar defects, and even crack-like features.

It cannot be emphasized too strongly that when composite materials are used to reinforce unconventional applications pipeline operators should carefully consider the demands to be placed upon the repair. This includes not only the loading itself, but limitations of the composite reinforcement such as strain capacity, maximum operating temperature range, and adhesion to the pipe. It is the author's opinion that when these types of issues are questioned on the front end of the design process and coupled with a rigorous assessment process, technically-sound composite reinforcement are produced. This is also consistent with federal pipeline regulations relating to pipeline repair, stating that when composites are used pipelines must be *repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe*.[10] There is a rich history of successful composite reinforcements that have utilized the rigorous Engineering Based Integrity Management Program presented in Appendix A.

[10] Federal Register: December 14, 1999 (Volume 64, Number 239)] {Rules and Regulations] {Page 69660-69665]

Table 6-1: Component Repair Data Sheet

This Component repair data sheet will form the basis of the client's scope of work and be used in the preparation of a design solution. One sheet shall be completed for each type of repair required.
Where possible, (digital) photographs of the defective areas should be provided.

Customer Details				
Contact				
Company				
Address				
Postal Code		Country		
Telephone				
Fax				
E-mail				
Job reference				

Component Details				
Component supports	e.g., buried, hangers, pipe racks, sleepers, thrust blocks			
Accessibility				
Location	e.g., inside, outside			
Quantity				
Component identification				
Component reference				
Component specification				
Material / grade				
External Diameter				
Wall thickness				
Medium				
Operating temperature	Minimum		Maximum	
Component coating (existing)				

Risk Assessment

Repair Requirements (see para. 1.2)	
Repair type	e.g., A or B
Required repair lifetime	
Other data	

Component loading	Operating	Design	Test	Comments
Pressure				
Axial				
Bending Moment				
Other				

GENERAL NOTES:

(a) For any original design calculations, component isometrics shall be appended to this data sheet.
(b) Loads shall be defined as either "Sustained" or "occasional" in the Comments column

Component Repair Data Sheet (Cont'd)

Details of Defect Area

Attach drawings of process system, inspection reports, etc., where available. Indicate any access restrictions and proximity to other equipment.

Repair specification				
Type of defect				
Nature of defect				
Current Size	Area		Depth	
Projected Size	Area		Depth	
Cause	Corrosion		Erosion	
Effect	External		Internal	
	Perforated			
MAWP				

GENERAL NOTE: MAWP/MAOP is the maximum allowable working/operating pressure as defined in ASME B31G, API 579/ASME FFS-1, BS 7910, or other calculation method.

Anticipated Conditions During Implementation of Repair

Pipe temperature	Minimum		Maximum	
Ambient temperature	Minimum		Maximum	
Humidity				
External environment				
Constraints				

Facilities to be Provided by Client / Installation (surface prep., etc.)

Other Information

GENERAL NOTE: This should include any remarks on previous repairs, fire protection requirements, available design calculations, etc.

Prepared by:____ Date:_______________

Table 6-2: Checklist for Verifying Proper Composite Repair Installations

Check List – Performance Verification

NAME: ______________________________

COMPANY: ____

LOCATION: ____

DATE: ______________________________

EVALUATOR/INSTRUCTOR: ______________________________

Item	Required Task	Yes	No	Notes
1	Determine location to be repaired.			
2	Confirm external damage.			
3	Determine axial length of repair and required thickness (i.e. number of wraps).			
4	Perform surface preparation.			
5	Establish a work area.			
6	Confirm ambient & pipe surface temperatures and record in *Notes*.			
7	Measure the circumference of the pipe.			
8	Measure the axial length of the repair area. Add 2 inches (or more) for the length of the composite material.			
9	Cut the composite material to the proper length.			
10	Abrasive blast and wipe the repair area on the pipeline with solvent.			
11	Mix the filler material.			
12	Mix the resin (if applicable).			
13	Apply the filler material to fill to all voids, pits, welds, etc. in the repair area.			
14	Saturate the composite material with the resin, making sure 100% coverage.			
15	Place the saturated composite material on the installation tubes for handling purposes.			
16	Apply a primer coat of the resin onto the entire pipe surface repair area.			
17	Install a straight and even first wrap of the composite material.			
18	Remove all wrinkles from the composite cloth as it is installed.			
19	Continue wrapping, straight and even, until the required number of wraps is installed. Ensure proper overlap of the wraps.			
20	Confirm removal of all wrinkles.			
21	Mix additional filler material.			
22	Apply the filler material to all seams (edges) around the pipe, both edges of the repair and at the trailing end of the composite.			
23	Monitor the curing process until an acceptable level of cure has happened.			
24	Verify the thickness of the as-installed composite.			
25	Clean work area and demobilize.			

7.0 CLOSING COMMENTS

This document has been prepared by ADV Integrity, Inc. for Dominion Energy to provide guidance in using composite repair systems to repair and reinforce high pressure gas pipelines. The presentation has included results from previous research programs, as well as insights obtained in evaluating the use of composite materials for the pipeline industry.

There are several important conclusions associated with the current body of work.

- Prior research has shown that when properly-designed and installed, composite materials are effective in restoring the integrity of damaged pipe sections. Loading of interest has included internal pressure (static burst and cyclic fatigue), axial tension, and bending.

- Although by definition repair systems qualified to meet the requirements of standards, such as ASME PCC-2 and ISO 24817, can be used to reinforce corrosion subjected to static pressures, any additional loading conditions or anomalies will require supplementary full-scale destructive testing. Examples of additional loads include cyclic pressures, axial tension, and bending loads. This is one of the major points of contention in industry; just because a system is qualified to repair one type of defect does not necessitate that it is qualified to repair all defects.

- Any new composite repair technology used by Dominion should be, as a minimum, subjected to the testing requirements specified in ASME PCC-2. Completing the additional comprehensive testing efforts, such as those associated with the inter-layer strain and pressure cycle fatigue tests, are strongly encouraged. The goal is to reduce risk in the deployment of composite technologies by fully-understanding the range of performance capabilities they possess.

- When failures have occurred with composite repair systems, the primary causes of failure are poor installation techniques and not allowing the repair to cure properly before the pipeline system is placed back in service.

Dominion is encouraged to require its composite repair suppliers to provide thorough documentation that includes material traceability. This helps ensure that what is being installed on the pipeline is consistent with what has been committed by the manufacturer. All composite systems should be installed by a certified applicator in accordance with a written procedure that is available on site and undergo adequate inspection before being placed into service. Finally, all materials used in a composite repair should be properly-marked with shelf and pot life information and batch number information for traceability.

8.0 REFERENCES

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17. 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.
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Appendix A: Engineering-Based Integrity Management Program

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.

Proceedings of the ASME 2014 Pressure Vessels & Piping Conference
PVP2014
July 20-24, 2014, Anaheim, California, USA

PVP2014-28256

DEVELOPING AN ENGINEERING BASED INTEGRITY MANAGEMENT PROGRAM FOR PIPING, PIPELINES, AND PLANT EQUIPMENT

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

Julian Bedoya
Stress Engineering Services, Inc.
Houston, Texas
julian.bedoya@stress.com

ABSTRACT

Establishing integrity for piping and pipelines requires an understanding of the specific threats, their relationship to the overall condition of the system, and the mitigating measures required to assure safe operation. In the past, industry has relied on years of research and experience to develop a set of tools to analyze these threats and apply conservative solutions to ensure integrity and fitness for service. An effective integrity management program as discussed in this paper, known as the Engineering Based Integrity Management Program (EB-IMP), provides operators with a resource for integrating inspection results, analysis, and testing to qualify the components within a pressurized system.

This paper presents a detailed discussion on how experience, advances in analytical techniques, experimental methods, and engineering rigor are combined to develop a tool to characterize and ensure system integrity. Several case studies are included to demonstrate how the EB-IMP method was used to evaluate the integrity of a piping system, as well as rail gondola cars used to transport coal. The intent with the approach presented in this paper is to foster further developments for advanced integrity management efforts.

INTRODUCTION

Managing integrity for piping and pipelines requires greater rigor than in previous years. The pipeline operators' goal is to continue operating an aging infrastructure without incident, while also meeting increasing regulatory requirements and optimizing integrity dollars. Industry currently has the basic tools to solve the simple or common integrity threats. It is the authors' observation that many pipeline companies perform integrity management using in-house methods or resources developed by consultants. As one would expect, much of this work is based on prior research and experience in dealing with a particular anomaly. Prior research has addressed the severity of plain dents by research organizations such as The Pipeline Council International, Inc. (PRCI) [1] and the American Petroleum Institute (API) [2]. Much of this work has been based on experimental results or numerical modeling such as finite element analysis.

Over the past decade, increased emphasis has been placed on the importance of performing integrity management assessments. This is due in part to regulatory activity, but also to recognizing the cost associated with downtime, as well as safety-related issues. This paper has been developed to present ideas associated with the development of an Engineering-Based Integrity Management Program (EB-IMP). This program is based in part on the principles embodied in the API 579-1/ASME FFS-1 *Fitness for Service* document [3]. At its core, API 579-1/ASME FFS-1 makes use of a three-level assessment process to evaluate the fitness for service of a particular component or system. Much of this work was driven by the downstream needs in U.S. refineries; however, there are several sections within this document that are applicable to pipelines including sections on corrosion in field bends and evaluating the effects of seam and girth welds in dents.

This paper describes a five step process for evaluating pipeline imperfections based on the EB-IMP. Figure 1 is a flow chart of the proposed process that builds on the basics of API 579-1/ASME FFS-1. This paper includes details on how companies can use the EB-IMP to evaluate the integrity of a selected anomaly using a methodology that integrates analysis and testing methods, as well as using prior experience and regulations set forth in the appropriate codes and standards.

The organization of this paper includes a *Background* section that provides for the reader details on the importance of the EB-IMP and its benefits for the pipeline industry. Discussions are also provided on how the EB-IMP is organized and what is involved in each stage of the five step process. Case studies are provided that demonstrates how the proposed EB-IMP method was used to evaluate the failure of a cold reheat line in a power plant and a case study that highlights engineer efforts conducted to evaluate failures in gondola cars used to deliver coal to power plants.

BACKGROUND

Integrity assessment has always been a part of operations and maintenance activities. As the plant piping and pipeline infrastructure has aged, industry first developed basic tools and as their importance became apparent, these tools improved to meet the increasing needs. Then as integrity questions were raised, assessment methods were developed for specific anomalies. Although EB-IMP was developed primarily for the pipeline industry, it applicability to piping in refineries and plants is certainly appropriate; especially considering its foundation on API 579-1/ASME FFS-1.

This section of the paper provides a brief discussion on how integrity management is currently performed and advances that have taken place using improved technology.

Basic Assessment Tools

The natural gas and liquid transmission pipeline industries have embraced the use of new technologies and strived to implement improvements to ensure safe pipelines. There are several examples that can be cited to demonstrate this point. One such example is pipeline corrosion. Industry first gathered wall thickness data using low-resolution metal loss magnetic flux leakage (MFL) in-line inspection (ILI) tools.

The results from these tools were recovered via charts and many man-hours of effort were spent to analyze the charts using tables based on conservative engineering and research results. The results from these analyses provided information on anomalies and indicated where resources should be directed to conduct physical examinations of the pipeline. As the performance of tools improved using better sensors, data storage and analysis, the information quantity and quality available for analysis grew exponentially. Currently, data is pre-processed on-board the ILI tool, analyzed in detail by the experts working for the tool supplier, and then provided to the pipeline company with software to further review the results for use in making decisions regarding pipeline integrity and remediation requirements.

Other integrity threats have followed similar paths over the years. For example, ILI technology that is used to find mechanical damage, selective-seam corrosion, and cracking has improved significantly over time.

Refined Assessment Tools

In conjunction with ILI analyses, pipeline companies have used software applications, such as RSTRENG, to make repair decisions for corrosion in straight pipe. While improvements have been made to RSTRENG, no developments have taken place to address corrosion in pipe fittings. Similarly, other threats like mechanical damage and dents have been evaluated using prescriptive, one-size-fits-all solutions written into federal codes and industry pipeline standards such as ASME 31.8. For example, the criteria used for decision making regarding plain dents is the dent depth to pipe-diameter ratio. These simplistic analysis methods do not consider dent profile details (i.e. curvature or sharpness of the dent), pipe properties, and pipeline operating conditions when making decisions on necessary repairs. While these generic analyses can generate information for making IMP decisions, they often result in recommending unnecessary repairs. The repairs are then made using simple but effective methods such as steel sleeves or replacement of the damaged pipe. In recent years steel sleeves have been supplemented with composite repair sleeves.

As will be presented, the proposed EB-IMP offers industry an alternative or improvements to conventional integrity management approaches. The uniqueness of the EB-IMP is based in large part on the inclusion of full-scale testing, when appropriate, to reduce the potential uncertainties in numerical modeling and provide greater confidence for the operator in understanding what conditions can lead to failure of the pipeline. By understanding failure modes, industry can select appropriate design margins to ensure safe operation, while at the same time not imposing overly-burdensome safety margins that force operators to use unreasonably low pressure levels. Another important element of the EB-IMP is that it includes developing repair solutions to extend the useful life of pipelines with known imperfections.

DEVELOPMENT OF AN EB-IMP SOLUTION

API Recommended Practice 579, Fitness-For-Service, was developed for the refining and petrochemical industry in 2000 and takes advantage of improvements in inspection and analysis by providing a basic method for assessing "metallurgical conditions and analysis of local stresses and strains which can more precisely indicate whether operating equipment is fit for it's intended service". These analyses address integrity concerns arising from historical design or fabrication imperfections and/or deterioration as a result of service conditions such as cracking or corrosion.

Two elements are not explicitly addressed in API-579. The first concerns the use of experimental methods or in situ measurement techniques to evaluate integrity. The other missing element concerns the development of repair techniques for the remediation of sub-standard equipment. It is recognized that the former might be a challenge in plant environments (e.g. performing a full-scale burst test on a $2 million platform reactor is not practical); however, full-scale testing is ideally-suited for pipelines where materials and anomalies can be evaluated apart from the pipeline system. In this regard, one purpose of the proposed EB-IMP solution is to analyze relevant test data and then develop cost-effective remediation methods to address integrity concerns. The resulting five step process provides operators with a complete solution for the specific threat with the intent of meeting code requirements for a reliable engineering solution.

Referring once again to Figure 1, the reader is encouraged to review the five steps involved in the assessment process. A body of text is included in this figure that reads:

> *After having completed the five step process in evaluating a specific pipeline anomaly, the objective is to <u>develop a general purpose assessment tool</u> that permits a general evaluation of similar imperfections. In order to do this, the tool creator must have a firm understanding of the respective anomaly including <u>critical variables</u> and potential <u>modes of failure</u>.*

As noted in this statement, the intent after having completed all five steps in evaluating a particular pipeline imperfection is to look for important variables and patterns that permit the development of a general tool. If this is not done, the operator fails to build on existing knowledge and will be forced to repeat similar assessments in the future. The better option is to develop a general tool that permits the assessment of a wide range of variables.

The sections that follow provide specific details on each of the five levels involved in the EB-IMP process. As stated previously, the intent in this exercise is the eventual development of an assessment tool that is field friendly. In the pipeline industry one of the best examples of a useful tool was the development of ASME B31G [6] and eventually RSTRENG [7] for assessing the severity of corrosion in a given pipeline. The critical variables identified prior to this study were corrosion depth and length, along with information on the pipe such as diameter, wall thickness, and grade.

Collecting Critical Data

For most integrity assessments of buried pipelines, the first step is often ILI inspection of the pipeline to determine where additional scrutiny is required. In plants where piping is accessible, a wide range of inspection technologies are available including radiography, ultrasonic, and eddy current. Following identification of the segment of concern the detailed design, operating conditions and field measurements are gathered. These details are then used for the analysis. The data gathered will be used to determine the extent of the effort and perform the final analysis required.

For the proposed EB-IMP assessment method, collecting data will result in identification of critical variables. It might be that during this process, the operator will be required to perform a literature search to determine what variables govern the severity of a given pipeline anomaly. An example of this was encountered by Alexander and Kulkarni in studying the severity of wrinkle bends. They found through research by Leis et al that the critical parameters that govern the fatigue life of wrinkles is their height, *h*, and length, *L*. Using this information, Alexander and Kulkarni developed a tool that permitted an assessment of wrinkles having h/L ratios from 0.1 to 0.5 and pipe to diameter wall thickness ratios ranging from 50 to 100 [11].

The quality of effort in this stage of the effort is extremely important to ensure the successful completion of the EB-IMP and deployment of a general-purpose tool useful for future evaluations.

Level I Analysis – Basic

The Level I effort involves the most basic form of an analysis that is possible. Typically, this includes performing an assessment based on industry codes or standards. For most pipeline operators this will mean referencing the original construction codes like ASME B31.8 [8] for gas pipelines and ASME B31.4 [9] for liquid pipelines.

Level II Analysis – Detailed

The analysis efforts associated with a Level II analysis requires more detailed information than required for a Level I assessment. The efforts involved in this phase are more complicated and the results are less conservative than those calculated using Level I methods. Examples of what might be involved in a Level II assessment would be calculations based on closed-form solutions such as those contained in API 579-1/ASME FFS-1 or other engineering resources. This work is typically performed by an engineer experienced in pipeline design and operation.

Level III Analysis – Numerical (Finite Element Analysis)

When the Level I and II analyses indicate that either the operating pressure must be re-rated in the pipeline or that a repair is necessary, it is possible to perform a Level III assessment. Numerical methods such as finite element analysis are the basis for a typical Level III assessment. The level of rigor associated with this effort is significant when compared to calculations completed as part of either a Level I or Level II assessment. On the other hand, the reward for completing a Level III analysis is a reduction in the safety margin associated with the previously two levels and a greater understanding about the actual load capacity of the pipeline or component.

As a point of reference, a Level I assessment will provide the design pressure for a given pipeline system. However, a Level III assessment calculates the ultimate pressure for the pipeline and a design pressure is then calculated from that value based on a given design margin. In this regard, the operator has a far greater understanding about the actual load capacity of his pipeline and the safety associated with his operation of the line. A limit state approach such as embodied in API RP 1111, as opposed to the earlier-referenced B31 codes, is applicable as it incorporates the ultimate capacity of the pipeline. This can be calculated either analytically using either the API RP 1111 closed-form equations or numerically calculated using finite element analysis. Additionally, as will be discussed in the Level IV (Testing) discussion that follows, full-scale testing can be used to determine the limit state condition. This approach not only improves confidence in the calculated results, but also facilitates regulatory approval if required.

It is likely that the eventual EB-IMP general-purpose tool development will rely heavily on the finite element models generated as part of this phase of work. Typically, the original assessment looks only at one specific set of conditions for a given anomaly, whereas the FEA work associated with the general tool development considers a range of variables and operating conditions.

Level IV - Testing

The results of the engineering and FEA analysis can be confirmed via a testing program. Alexander has developed recommendation for the pipeline industry in using testing methods to augment integrity management efforts [10]. Testing can involve either pipe material removed from service or pristine pipe, depending on the desired outcome of the study. For example, if a pipeline company is interested in the performance of vintage girth welds subject to cyclic pressure service, it would be prudent to remove girth welds from the field and test them. On the other hand, if an operator is merely trying to quantify the relative severity of different-sized dents in a girth weld, it would be possible to fabricate samples using modern pipes and welding techniques and then install the dents prior to testing. Fundamentally, the question that must be asked prior to testing is if the interest lies in actually quantifying material properties or only seeking general trends such that qualification of an anomalies' severity is sufficient.

As an example of testing as part of a Level IV assessment, a cyclic testing program can be used to simulate future service conditions of the system over a time period (i.e. representing 25 years of service). Cyclic testing of an unrepaired component can be used to predict the effects of future service on the component. When the component passes burst test requirements and cyclic testing shows little or no degradation over time these results can be used to support continued use of the unrepaired component. When unsatisfactory results are obtained from the cyclic testing, the decision to repair can be confirmed. The repaired component can also be cyclically tested to demonstrate future serviceability. The un-repaired versus repaired results can also be compared to evaluate improvements made by making the repair. The final step following cyclic testing should be burst testing to show that the component has an acceptable margin of safety and is fit for future service.

An additional benefit in using cyclic testing is that the results can be used to develop EB-IMP reassessment intervals for components that might fail due to cyclic loading that include degradation mechanisms such as mechanical damage, cracks, dents and wrinkles.

Level V - Repair solution design

Remediation of common integrity threats can be accomplished using accepted repair procedures and these methods are, for the most part, well suited and conservative. The information gathered and the analysis can also be used to develop a repair procedure tailored to meet the specific needs of the situation. These tailored repair solutions offer safe, cost-effective solutions in lieu of the one-size-fits all cut-out method of repair. The design for the repair can also be modeled using an FEA to evaluate suitability.

Tool Development

The results associated with the five step process can be used to develop a general tool for making judgments on the integrity of a given imperfection. This will typically involve the development of software or simple calculation tools that can be used by operators to assess and make repair decisions for other similar integrity concerns. The tool is developed to replace the five step process, thus providing pipeline operators with a simple documentable EB-IMP tool to make assessment and repair decisions.

As mentioned previously, it is essential when developing a general tool that the critical variables be used as the basis for choosing input parameters. Insights gained during the analysis and testing phases of work will confirm the validity and importance of the previously identified variables. Methods such as the Buckingham-Pi Theorem can be used to generally assess the contribution of a given variable to its effect on pipeline integrity.

CASE STUDIES

To illustrate the EB-IMP assessment process two cases are presented. The first is a study performed on a catastrophic failure that occurred in a 30-inch diameter cold reheat (CRH) steam line at the W. A. Parish Plant. The study involved numerical modeling involving computational fluid dynamics and finite element analysis, field instrumentation, and a full-scale mock-up test.

The second case study, although not specifically involving piping, involved an assessment performed on coal gondola cars that developed buckles in their top chords. The study involved finite element modeling and field instrumentation used to measure stresses during transportation and dumping of the coal.

Cold Reheat Line Failure Case Study

After a catastrophic failure that occurred in a 30-inch diameter cold reheat (CRH) steam line at the W. A. Parish Plant, Texas Genco conducted a study to determine the cause of the failure. The incident occurred at approximately 12:10 PM on July 15, 2003 and resulted in a catastrophic failure that scattered components around the plant in a radius of 1,200 feet. Reliant Resources and Texas Genco conducted their own failure investigation that involved metallographic examinations, inspection of the fracture surfaces, review of operating conditions at the time of failure, and studies related to the weld profile of the CRH line.

Figure 2 and Figure 3 are photographs from the failure analysis report showing the region where the failure occurred (on the inside surface at the toe of the weld) and a close-up view of the fracture surface. Of specific interest are the three fracture zones clearly shown in Figure 3 and listed below.

- Region 1 (76% of wall) - initial smooth fatigue fracture zone
- Region 2 (16% of wall) - second rougher fatigue fracture zone
- Region 3 (8% of wall) - final overload fracture zone that failed on July 15, 2003

The engineering efforts included studies using computational fluid dynamics (CFD) to address how droplet sizes from the attemperator[1] might impact downstream behavior of the piping system. Figure 4 and Figure 5 show results from the CFD analysis showing distribution of water considering droplet diameters of 0.1 and 10 mm. As expected, the smaller droplets are distributed farther downstream from the attemperator. Figure 6 plots surface temperature distribution on pipe considering a 1 mm droplet

Follow-on work involved conducting a mock-up testing to study the performance of the attemperator, as well as field monitoring using high temperature strain gages, accelerometers, and thermocouples. Figure 7 is a diagram showing the location of high temperature strain gages installed on the CRH during actual service, while Figure 8 plots stresses based on strain measurements near the failure location. Noteworthy in this plot are the stress changes that occur during operation of the CRH line.

The data obtained from the field monitoring efforts, along with process data provided by Texas Genco, were used to perform finite element analyses. The finite element work involved the calculation of static stresses as well as transient stresses generated by cycling of the attemperator (thermal stresses) and vibration of the line (mechanical stresses). Fracture mechanics was used to determine the amount of time required for crack initiation and propagation to failure. Figure 9 provides a global view of the line showing the von Mises stress contour plot including makeup, gravity, pressure, and thermal loading. Figure 10 is a detailed stress contour plot of the weld cross-section that includes the calculated stress concentration factor (SCF) of 4.35.

What was demonstrated in this work is how a failure investigation can be coupled with testing, monitoring, and analyses to not only determine causes of failure, but identify specific steps that can be taken to prevent future failures. The analysis and monitoring efforts clearly demonstrated the operating conditions that were required to produce the failure. Additionally, the failure reinforced the importance of regular inspection of piping systems; even those high energy piping systems such as the cold reheat lines that are not normally associated with catastrophic failures. By integrating the important lessons learned in this study, the power industry can ensure the safe operation of its cold reheat lines and reduce the potential for catastrophic failures.

Coal Gondola Car Case Study

A power utility company experienced a series of isolated top chord buckles in their coal gondola cars. A study was conducted to determine the buckling capacity of gondola cars that are responsible for transporting and dumping coal. Photographs of buckled top chords are shown in Figure 11. Experience has shown that the top chords of coal gondolas can buckle under certain loading conditions; driven by compressive loads in these structural members. To determine the structural integrity of coal cars an investigation was undertaken using a range of tools that included finite element modeling, stress analysis during transport and coal dumping using on-board strain gages, and an assessment of loads during the dumping operation.

Finite element modeling and limit analysis were used to quantify the loads responsible for the buckled top chords. Figure 12 shows the geometry of the finite element models, while Figure 13 shows both the displaced shape and a von Mises stress contour. One of the objectives in the numerical modeling effort was to evaluate top chord reinforcing options. The optimized solution determined that welding 5-inch x 3-1/2-inch x 3/8-inch thick angle iron was sufficient to

[1] An attemperator (or Desuperheater) reduces steam temperature by bringing superheated steam into direct contact with water. The steam is cooled through the evaporation of the water injected into the steam flow.

ensure that buckles would no longer occur in the top chords. The analysis also compared results evaluating benefits of reinforcing versus top chord replacement. In terms of the EB-IMP, determining options for the reinforcement of the top chord is associated with the Level 5 of the EB-IMP.

To quantify stresses generated in the gondola cars during transportation and dumping, strain gages were installed. Strain gages were installed on the top chord, as well as the side walls of the car. Figure 14 includes data collected during the study. A Campbell data logger was used to record data during various transportation and dumping loading phases.

The benefits of this investigation are several-fold. First, the utility company was able to determine the buckling capacity of the coal gondolas. Secondly, they were able to assess the loads imparted to the railcar during transportation and dumping. And lastly, they were able to optimize repair options for cars that had been damaged by buckling of the top chords. This body of work is a clear demonstration of the benefits associated with using engineering analysis, testing, and monitoring to assess the structural integrity of coal gondolas and develop appropriate mitigation techniques.

DISCUSSION

The implementation of the EB-IMP assessment process produces safer pipeline, piping, and structural systems. The process is designed to address the specific integrity assessment needs identified by using actual anomaly data to tailor an analysis of the integrity threat. Once the actual details of the threat are collected, a specific appropriate engineering analysis can be performed that will result in a safe, yet not-overly conservative result. Once the level of threat is established and quantified, a repair for a specific component can be designed if required.

It is the authors' observation that many integrity management programs are based on a one-size-fits-all approach. The problem with this approach is that the resulting conclusions and subsequent decisions have the propensity to be overly-conservative and not reflect actual conditions of the system. This is one reason that testing has been so heavily emphasized in the development of the EB-IMP. Without a screening tool, like RSTRENG for corrosion (which was based on a significant number of full-scale burst tests), time and effort is spent analyzing anomalies that are insignificant, while critical anomalies wait. Similarly, when maintenance dollars are spent on the repair of anomalies that are not a threat, other more critical anomalies are not repaired.

When the integrity assessment process involves repeating the analysis and repair of other similar components, it is appropriate and prudent to develop a general-purpose assessment tool. The tool can be used first as a screening tool and then provide guidance on the repair if required.

Further, testing of components removed from the field provides an important validation of the specific overall EB-IMP assessment process. First by testing a flawed component the analysis can be verified. Testing also demonstrates the repair meets long tern service requirements. Testing demonstrates the tool developed provides a conservative solution and reduces the likelihood that any over-conservatism might exist.

CONCLUSIONS

This paper has presented the fundamental elements associated with the development and use of an Engineering-Based Integrity Management Program and provides the reader with the basics required to perform similar assessments. The uniqueness of this approach is the integration of actual pipeline data, coupled with analysis and testing efforts, to generate a tailor-suited engineering based process that addresses specific threats to pipeline integrity. The result of this effort is that the EB-IMP process can address single critical integrity threats or the process can be used to develop a general-purpose tool to address a range of threats identified within a system.

The EB-IMP process is based on basic engineering principles followed by testing to confirm analysis results and reduce the potential for generating overly-conservative restrictions on system maintenance and operation. The result of this effort is a process, and tool when appropriate, that remediates integrity threats, optimizes maintenance dollars, and generates the documentation for in-house due-diligence efforts that can then be used to demonstrate system integrity to regulators and other interested parties.

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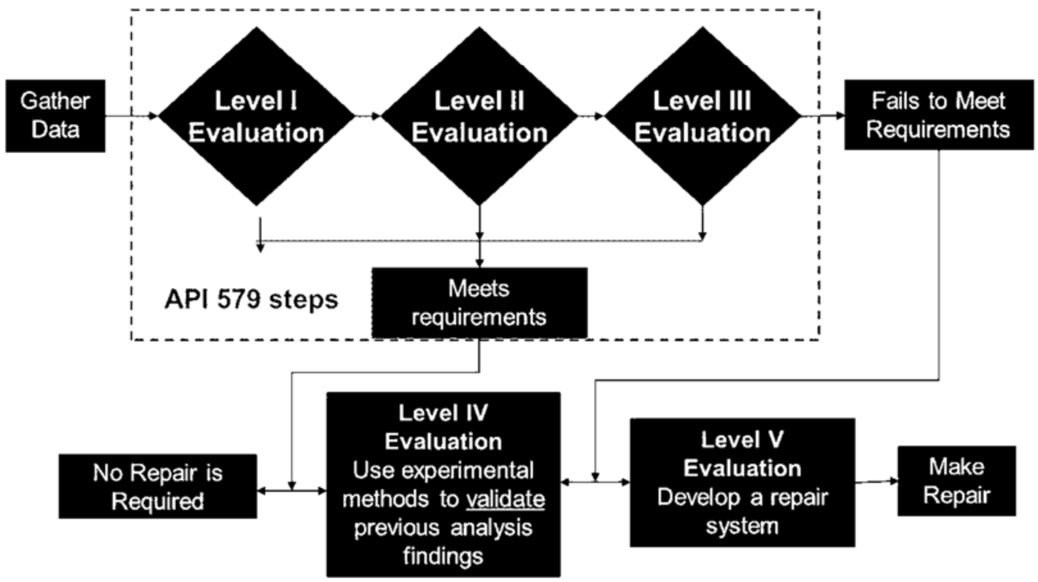

Figure 1: Flow chart showing elements of the Engineering Based Integrity Management Program

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Figure 2: Horizontal spool piece showing fatigue-cracked seam weld

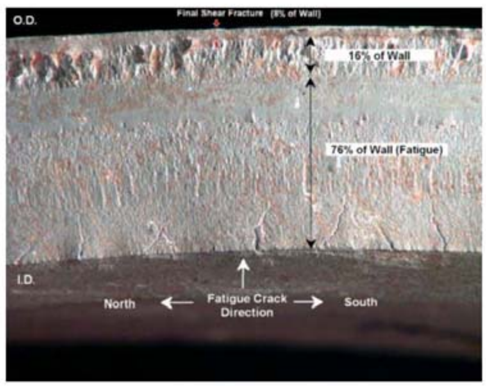

Figure 3: Close-up view of fracture showing distinct fracture zones

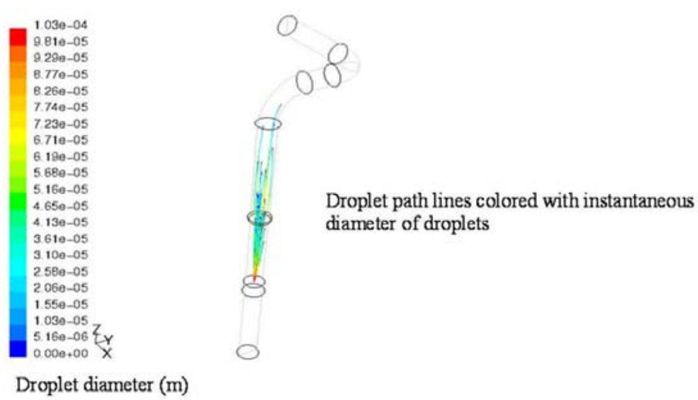

Figure 4: Droplet path lines with 0.1 mm droplet diameter at injection

7

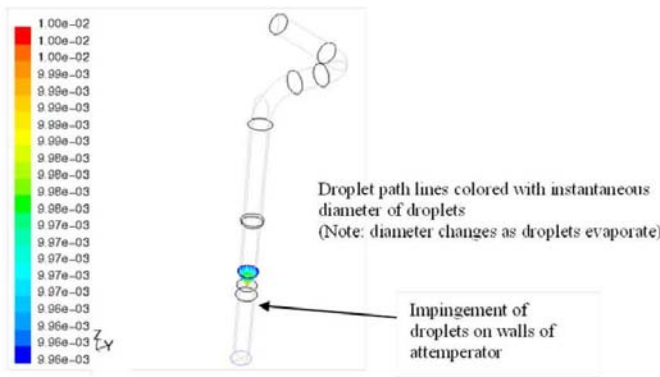

Figure 5: Droplet path lines 10 mm droplet diameter at injection

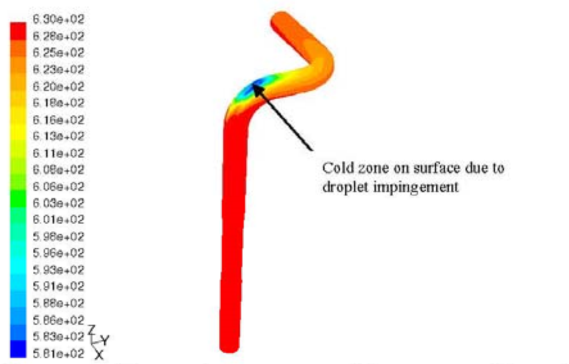

Figure 6: Surface temperature distribution on pipe with 1 mm droplet

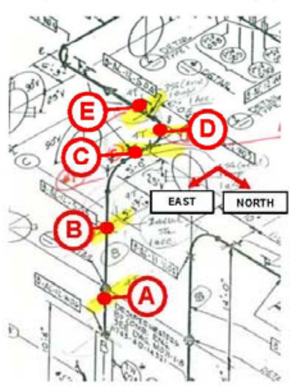

Figure 7: Locations A through *E* for instrumentation (strain and temperature)

8

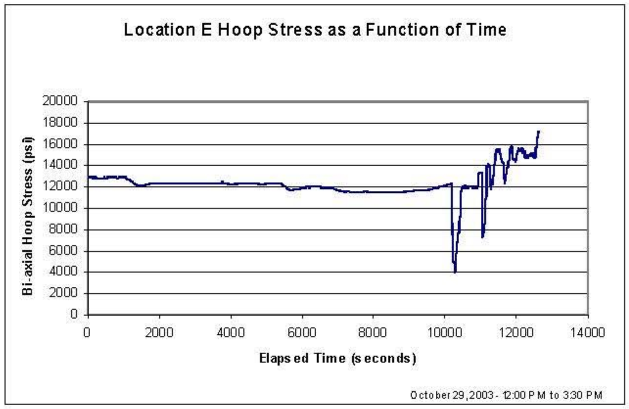

Figure 8: Hoop stress recorded near failure region

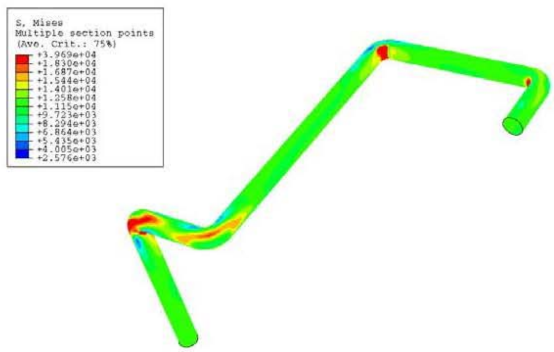

Figure 9: Von Mises Stress contour plot with makeup, gravity, pressure, and thermal loading

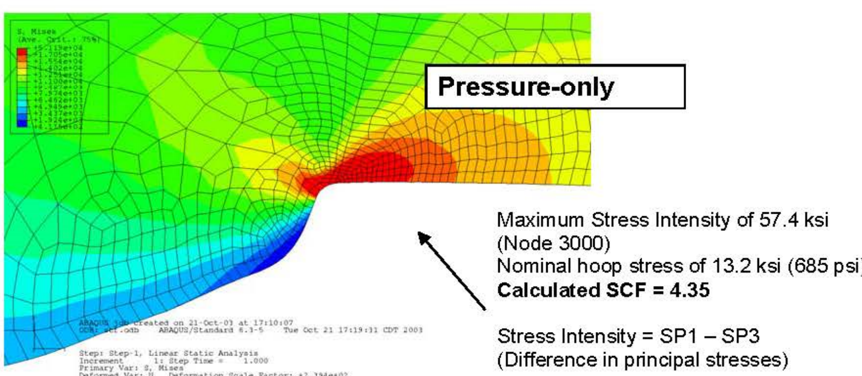

Figure 10: Detailed stress contour plot including SCF value (weld cross-section)
(Fracture initiated at the toe of the weld as shown in the above figure)

Figure 11: Photographs of buckled top chord and associated fracture

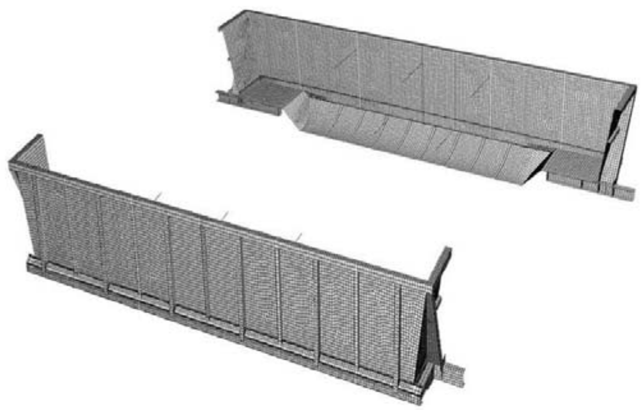

Figure 12: Mesh for finite element model of gondola car

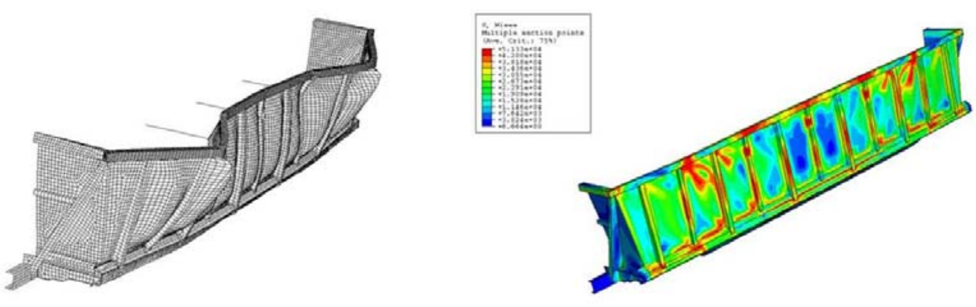

Figure 13: Finite element model showing displaced shape and contour stresses

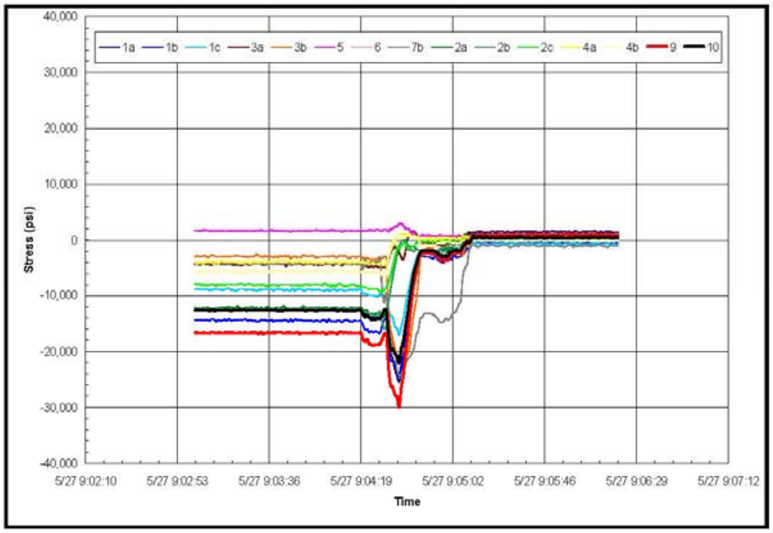

Figure 14: Stress based on strain gage measurements made using on-board data logger

Appendix B: ASME PCC-2 Components Repair Data Sheet

(ASME PCC-2, Repair of Pressure Equipment and Piping, Article 4.1, Mandatory Appendix I)

Component Repair Data Sheet

This Component repair data sheet will form the basis of the client's scope of work and be used in the preparation of a design solution. One sheet shall be completed for each type of repair required.
Where possible, (digital) photographs of the defective areas should be provided.

Customer Details			
Contact			
Company			
Address			
Postal Code		Country	
Telephone			
Fax			
E-mail			
Job reference			

Component Details				
Component supports	e.g., buried, hangers, pipe racks, sleepers, thrust blocks			
Accessibility				
Location	e.g., inside, outside			
Quantity				
Component identification				
Component reference				
Component specification				
Material / grade				
External Diameter				
Wall thickness				
Medium				
Operating temperature	Minimum		Maximum	
Component coating (existing)				

Risk Assessment

Repair Requirements (see para. 1.2)	
Repair type	e.g., A or B
Required repair lifetime	
Other data	

Component loading	Operating	Design	Test	Comments
Pressure				
Axial				
Bending Moment				
Other				

GENERAL NOTES:

(a) For any original design calculations, component isometrics shall be appended to this data sheet.
(b) Loads shall be defined as either "Sustained" or "occasional" in the Comments column

Component Repair Data Sheet (Cont'd)

Details of Defect Area

Attach drawings of process system, inspection reports, etc., where available. Indicate any access restrictions and proximity to other equipment.

Repair specification				
Type of defect				
Nature of defect				
Current Size	Area		Depth	
Projected Size	Area		Depth	
Cause	Corrosion		Erosion	
Effect	External		Internal	
	Perforated			
MAWP				

GENERAL NOTE: MAWP/MAOP is the maximum allowable working/operating pressure as defined in ASME B31G, API 579/ASME FFS-1, BS 7910, or other calculation method.

Anticipated Conditions During Implementation of Repair

Pipe temperature	Minimum		Maximum	
Ambient temperature	Minimum		Maximum	
Humidity				
External environment				
Constraints				

Facilities to be Provided by Client / Installation (surface prep., etc.)

Other Information

GENERAL NOTE: This should include any remarks on previous repairs, fire protection requirements, available design calculations, etc.

Prepared by:____ Date:________________

Appendix C: ASME PCC-2 Installation Requirements

(ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix VII)

Article 4.1, Mandatory Appendix VII Installer Qualification

(15)

VII-1 INTRODUCTION

The repair of components using composite laminates differs considerably from other repair techniques, and the quality of the installation depends strongly on satisfactory craftsmanship. Training and qualification of personnel are therefore key elements of a successful repair. This Mandatory Appendix outlines the minimum requirements for training, qualification, and approval of installers and supervisors/trainers for the specific Repair System.

NOTE: Supervisors and trainers have the same qualification requirements but may be different positions within the organization of the Repair System vendor.

VII-2 TRAINING

(a) Courses and training shall be arranged by or with the assistance of the Repair System supplier.

(1) The Repair System supplier may use qualified trainers to train installers and other supervisors.

(2) The Repair System supplier shall be responsible for the training of the supervisors/trainers.

(b) The basic course shall give a theoretical and practical introduction to the most important elements in the installation of a composite repair.

VII-2.1 Coursework (Installer)

(a) The course shall include training in

(1) definition of a Repair System
(2) terminology, types of repair
(3) hazards associated with pressurized systems
(4) health, safety, and environment
(5) surface preparation
(6) material preparation
(7) material application
(8) control of repair conditions
(9) quality control

(b) A written test covering the above subjects shall be taken and passed by the installer.

VII-2.2 Coursework (Supervisor/Trainer)

(a) The supervisor/trainer candidate shall be a qualified installer.

(b) The supervisor/trainer shall complete the following additional training:

(1) supervisor's/trainer's duties and responsibilities
(2) evaluation methods used in repair design
(3) health and safety
(4) installation checklist and hold points
(5) inspection of repairs

(c) A written test covering the above subjects shall be taken and passed by the supervisor/trainer.

VII-2.3 Installer-Specific Qualification

(a) Installers shall be qualified for each specific Repair System through practical tests for Type A and/or Type B.

(b) All specific approval tests shall be carried out in accordance with a written procedure, relevant to the specific Repair System and approved by the Repair System supplier.

(c) Qualification records shall be maintained by the employer of the Repair System installer.

VII-2.3.1 Type A

(a) Repair shall be applied to a pipe test specimen of at least 100 mm (4 in.) diameter.

(b) Repair shall pass visual inspection completed in accordance with para. 5.2 of Article 4.1 witnessed by a supervisor or instructor.

VII-2.3.2 Type B

(a) In addition to the requirements for Type A repairs, an identical test specimen to one of the nine from Mandatory Appendix IV (Article 4.1) shall be prepared.

(b) The specimen shall be subject to a pressure test as described in Mandatory Appendix IV (see Article 5.1 for guidance).

(c) The γ value of the test shall be calculated according to Mandatory Appendix IV.

(d) The calculated γ value shall be not less than γ_{LCL}.

VII-3 TRAINING RECORDS

(a) At the completion of an installer or supervisor/trainer course, a successful candidate shall be issued with a certificate by the qualified trainer providing details of the Repair System of concern.

(b) The employer of the Repair System installer shall keep a record of the completed training (e.g., logbook for each Repair System installer).

VII-4 REQUALIFICATION

(a) The type-specific qualification shall be valid for a period of 1 yr.

(b) If the installer has performed a documented installation witnessed by a supervisor during the year of type-specific qualification, then their qualifications may be renewed for another year, for a maximum of two renewals.

(c) If the installer has not performed a repair in the last year then they shall be requalified prior to applying further repairs.

(d) The installer shall complete the requalification process no less than once every 3 yr.

Appendix D: Surface Preparation Standards

Surface Preparation Standards

Your coatings supplier will always designate the degree of surface preparation required for the materials you are using. The basic standards for preparing metal substrates are a joint effort between the Society for Protective Coatings (SSPC) and the National Association of Corrosion Engineers International (NACE).

SSPC-SP1 Solvent Cleaning
Removal of all visible oil, grease, soil, drawing and cutting compounds, and other soluble contaminants from steel surfaces with solvent, vapor, cleaning compound, alkali, emulsifying agent, or steam.

SSPC-SP2 Hand Tool Cleaning
Removes all loose mill scale, loose rust, loose paint, and other loose detrimental foreign matter by hand chipping, scraping, sanding, and wire brushing.

SSPC-SP3 Power Tool Cleaning
Removes all loose mill scale, loose rust, loose paint, and other loose detrimental foreign matter by power wire brushing, power sanding, power grinding, power tool chipping, and power tool descaling.

SSPC-SP5 / NACE 1 White Metal Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter.

SSPC-SP6 / NACE 3 Commercial Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 66-2/3% of unit area, which shall be a square 3 in. x 3 in. (9 sq. in.). Light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating in less than 33-1/3% of the unit area is acceptable.

SSPC-SP7 / NACE 4 Brush-Off Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife.

SSPC-SP10 / NACE 2 Near-White Blast Cleaning
When viewed without magnification shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 95% of each unit area. Staining shall be limited to no more than 5 percent of each unit area, and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coatings. Unit area shall be approximately 3 in. x 3 in. (9 sq. in.).

SSPC-SP11 Power Tool Cleaning to Bare Metal
When viewed without magnification, the surface shall be free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products, and other foreign matter. Slight residues of rust and paint may be left in the lower portion of pits if the original surface is pitted. The surface profile shall not be less than 1 mil (25 microns).

Surface Preparation Standards

SSPC-SP12 / NACE 5 Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultra High- Pressure Water Jetting Prior to Recoating

This standard requires water jetting at high- or ultra high-pressure to prepare a surface for recoating using pressure above 10,000 psi. Water jetting will not produce a profile; rather, it exposes the original abrasive-blasted surface profile. Water jetting shall be performed to meet four conditions: WJ-1, WJ-2, WJ-3, and WJ-4, and a minimum acceptable surface shall have all loose rust, loose mill scale, and loose coatings uniformly removed.

SSPC-SP13 / NACE 6 Surface Preparation of Concrete

Provides requirements for surface preparation of concrete by mechanical, chemical, or thermal methods prior to the application of bonded protective coating or lining systems.

SSPC-SP14 / NACE 8 Industrial Blast Cleaning

Removal of all visible oil, grease, dust and dirt, when viewed without magnification. Traces of tightly adherent mil scale, rust, and coating residues are permitted to remain on 10% of each unit area of the surface if they are evenly distributed. Shadows, streaks, and discoloration caused by stains of rust, stains of mill scale, and stains of previously applied coating may be present on the remainder of the surface.

Surface Preparation Standards

Water Jetting Standards

SSPC-SP12 / NACE 5
Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultra High- Pressure Water Jetting Prior to Recoating

This standard requires water jetting at high- or ultra high-pressure to prepare a surface for recoating using pressure above 10,000 psi. Water jetting will not produce a profile; rather, it exposes the original abrasive-blasted surface profile. The specifier shall use one of the visual surface preparation definitions (WJ-1 to WJ-4) and one of the non-visual surface preparation definitions (SC-1 to SC-3) to specify the degree of visible and non-visible surface matter to be removed.

Pressure Categorization

Low-Pressure Water Cleaning (LP WC)
Cleaning performed at pressures less than 34 Mpa (5,000 psi)

High-Pressure Water Cleaning (HP WC)
Cleaning performed at pressures from 34 to 70 Mpa (5,000 to 10,000 psi)

High-Pressure Water Jetting (HP WJ)
Cleaning performed at pressures from 70 to 170 Mpa (10,000 to 25,000 psi)

Ultrahigh-Pressure Water Jetting (UHP WJ)
Cleaning performed at pressures above 170 Mpa (25,000 psi

Visual Conditions of Surface Cleanliness

WJ-1
Surface shall be free of all previously existing visible rust, coatings, mill scale, and foreign matter and have a matte metal finish

WJ-2
Surface shall be cleaned to a matte finish with at least 95% of the surface area free of all previously existing visible residues and the remaining 5% containing only randomly dispersed stains of rust, coatings, and foreign matter

WJ-3
Surface shall be cleaned to a matte finish with at least two-thirds of the surface area free of all previously existing visible residues (except mill scale), and the remaining one-third containing only randomly dispersed stains of previously existing rust, coatings, and foreign matter

WJ-4
Surface shall have all loose rust, loose mill scale, and loose coatings uniformly removed

Non-Visual Conditions of Surface Cleanliness

SC-1
Surface shall be free of all detectable levels of contaminants as determined using available field test equipment with sensitivity approximating laboratory test equipment. For purposes of this standard, contaminants are water-soluble chlorides, iron-soluble salts, and sulfates

SC-2
Surface shall have less than 7 µg/cm^2 chloride contaminants, less than 10 µg/cm^2 of soluble ferrous ion levels, and less than 17 µg /cm^2 of sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment

SC-3
Surface shall have less than 50 µg/cm2 chloride and sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment

Surface Preparation Standards

Surface Preparation by Substrate

	Iron or Steel	Galvanized	Aluminum	Pre-Finished Metals	Stainless Steal	Non-Ferrous Metals	Plastic – PVC/FRP	Concrete	Previously Painted Surfaces
SSPC-SP1 Solvent Cleaning	X	X	X	X	X	X		X	X
SSPC-SP2 Hand Tool Cleaning	X	X							
SSPC-SP3 Power Tool Cleaning	X	X						X	
SSPC-SP11 Power Tool Cleaning to Bare Metal	X								
SSPC-SP7/NACE 4 Brush-Off Blast Cleaning	X	X	X	X	X	X		X	X
SSPC-SP14/NACE 8 Industrial Blast Cleaning	X								
SSPC-SP6/NACE 3 Commercial Blast Cleaning	X								
SSPC-SP10/NACE 2 Near-White Blast Cleaning	X								
SSPC-SP5/NACE 1 White Metal Blast Cleaning	X								
SSPC-SP12/NACE 5 High-and Ultrahigh-Pressure Water Jetting Prior to Recoating	X			X			X	X	X
SSPC-SP13/NACE 6 Surface Preparation of Concrete								X	

Concrete can also be cleaned and prepared using ASTM D 4260 (Acid Etch – Floors), ASTM D 4258 (Solvent Cleaning), ASTM D 3359 (To Check Adhesion), and ASTM D 4259 (To Abrade Concrete).

Appendix E: Repair of Dents Using Composite Materials

Alexander, C., and Bedoya, J.
Repair of Dents Subjected to Cyclic Pressure Service Using Composite Materials
Proceedings of IPC2010 (Paper No. IPC2010-31524)
8th International Pipeline Conference
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REPAIR OF DENTS SUBJECTED TO CYCLIC PRESSURE SERVICE USING COMPOSITE MATERIALS

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

Julian Bedoya
Stress Engineering Services, Inc.
Houston, Texas
julian.bedoya@stress.com

ABSTRACT

For the better part of the past 15 years composite materials have been used to repair corrosion in high pressure gas and liquid transmission pipelines. This method of repair is widely accepted throughout the pipeline industry because of the extensive evaluation efforts performed by composite repair manufacturers, operators, and research organizations. Pipeline damage comes in different forms, one of which involves dents that include plain dents, dents in girth welds and dents in seam welds. An extensive study has been performed over the past several years involving multiple composite manufacturers who installed their repair systems on the above mentioned dent types. The primary focus of the current study was to evaluate the level of reinforcement provided by composite materials in repairing dented pipelines. The test samples were pressure cycled to failure to determine the level of life extension provided by the composite materials relative to a set of unrepaired test samples. Several of the repaired dents in the study did not fail even after 250,000 pressure cycles were applied at a range of 72% SMYS. The results of this study clearly demonstrate the significant potential that composite repair systems have, when properly designed and installed, to restore the integrity of damaged pipelines to ensure long-term service.

INTRODUCTION

Composite materials were originally used to repair corrosion in transmission pipelines; however, research in the 1990s conducted by the Gas Research Institute on the Clock Spring system demonstrated that composite materials can also be an effective means for repairing dents and mechanical damage. Additional tests were also performed that further demonstrated the capacity of composite materials in repairing dents. When used to repair dents, composite repair systems minimize the flexure that takes place in the dent. When the dent is restrained and prevented from moving during pressure cycling, the alternating strains are reduced and the fatigue life of the dent is extended.

In response to past successes in previous studies comparing different composite materials, a Joint Industry Program (JIP) was organized to experimentally evaluate the repair of dents using composite materials. The program was co-sponsored by the Pipeline Research Council International, Inc. and six manufacturers testing a total of eight different repair systems. Additionally, a set of unrepaired dent samples was also prepared to serve as the reference data set for the program. The dent configurations included plain dents, dents in girth welds, and dents in ERW seams (high frequency). Testing involved installing 15% deep dents (as a percentage of the pipe's outside diameter) where the dents were cycled to failure or 250,000 cycles, whichever came first. The test samples were made using 12.75-inch x 0.188-inch, Grade X42 with a pressure cycle range equal to 72% SMYS. Strain gages were also placed in the dented region of each sample and monitored periodically during the pressure cycle testing. The sections of this paper that follow include details on how the dent samples were fabricated, how the samples were tested and includes a detailed discussion on the results.

TESTING METHODS

Because the intent of the current study was to determine the level of reinforcement provided by composite materials, it was important that the severity of the dents be significant enough so that failure of the unrepaired dent sample would occur within a relatively small number of cycles. Using insights gained from prior studies [1, 2], a test matrix was selected with the intent of having fatigue failures occur in less than 10,000 pressure cycles, where the applied stress range was equal to 72% SMYS (Specified Minimum Yield Strength). Experience has shown that in order for this condition to exist, a severe level of strain must be induced during the dent deformation process. Therefore, to achieve this high level of strain the dents were generated using a 4-inch diameter end cap pressed into the pipe (15% of the pipe's outside diameter). An internal pressure (72% SMYS) was applied while the dent was held in place. The sections that follow provide details on the installation of dents, along with details associated with the composite repair installation activities.

Test Sample Phases of Work

Listed below are the specific steps that were employed during the test program. Note that the list has been broken into the following phases of work:

- Pre-test activities
- Dent installation
- Pressure cycling and monitoring
- Post-failure activities

Pre-test activities Listed below are the activities associated with the pre-test phase of work in the current test program.

1. Purchased 12.75-inch x 0.188-inch, Grade X42 pipe to achieved required sample length (28-ft per sample).
    a. Performed material testing including chemistry, mechanical properties (yield, ultimate, and elongation), and toughness (Charpy at 32°F and room temperature).
2. Marked orientation of ERW seam on each pipe as shown in Figure 1, as well as location for all six (6) dents in each pipe sample.
3. Pipe material was cut to achieve desired sample length.
4. Installed girth welds and end caps.
    a. The girth welds were X-rayed after indentation to determine if any cracks were present.
    b. Two girth welds and two end caps required per sample.

Dent Installation Listed below are the activities associated with the dent installation phase of work in the current test program.

5. Installed six (6) dents per sample having an initial dent depth of 15% using a 4-inch spherical end cap as the rigid indenter using the following process:
    a. The first dent was installed to a depth of 15% of the pipe's outside diameter (1.9 inches for the 12.75-inch OD pipe).
    b. The indenter was held in place while the sample was then pressurized to 72% SMYS (892 psi). In this regard, the simulated defect represents an in-service dent generated while the pipeline is operating.
    c. The load-deflection data was recorded for the six (6) dents in the **unrepaired sample only**.
    d. The indenter was removed while the sample was pressurized to capture the residual dent depth. Experience has shown that an initial dent depth of 15% in a 12.75-inch x 0.188-inch pipe typically rebounds after pressure has been applied to a final dent depth on the order of 3-5% (i.e. significant rerounding occurs).
    e. After the pressure was removed, the dent profile was measured as shown in Figure 2. These measured data can be used to calculate local bending strains in the dent.
    f. The above process was continued (steps a through d) to install the five (5) remaining dents – all dents were made with internal pressure.
    g. After all six dents were installed, 10 pressure cycles from 0 to 72% SMYS (0 to 892 psi) were applied after which the dent profiles were measured. Figure 3 shows the indenter in position prior to denting, while Figure 4 shows the level of deformation that remained after the 10th pressure cycle had been applied to one of the girth weld samples.
6. Inspected girth welds via X-ray after denting to detect if any cracks were introduced during indentation.
7. Sandblast pipes where composite materials will be installed.

Pressure cycling and monitoring Listed below are the activities associated with the pressure cycling and monitoring phase of work in the current test program.

8. Installed strain gages near dents in transition area on "halo" region of dent. Refer to details shown in Figure 1 for strain gage locations and associated numbering.
9. Composite repair materials were installed with no pressure in the pipe sample. Each manufacturer was responsible for designed their particular system.
10. Test samples were fatigue tested by applying cyclic pressures ranging from 0 to 100% MAOP (where MAOP is 72% of SMYS or 892 psi for the given pipe grade and geometry). Samples were cycled to failure or 250,000 cycles, whichever occurred first.
11. Strain gage data were recorded for 10 cycles at the following test intervals: start-up, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000 cycles (assuming the strain gages survive). The length over which data was collected was limited to either when the first fatigue failure occurs or when the strain gages stopped working. This is consistent with SES' typical data recording period for fatigue test samples.

Post-Failure Activities Listed below are the activities associated with the post-failure phase of work in the current test program.

12. As failures occurred, the failed leaking dent was cut out, the remaining sections were welded, and pressure cycling continued.
13. The cycles to failure for each dent were recorded. The unrepaired defects were visually examined and photographs were taken of the resulting fatigue cracks. For the defects repaired using composite materials, the pipe was cut outside of the repair to permit visual inspection of the internal surface of the pipe.
14. In addition to details on the dents, information was collected on the composite repair systems including:
    a. Composite material thickness.
    b. Length of composite.
    c. Composite material type (fiber and resin type).
    d. Design calculations from manufacturer (if available).
15. For the unrepaired samples, the final dent profiles were measured after all testing has been completed.

Composite Repair Installation

As noted previously, six manufacturers installed a total of eight different repair systems in the current program. Each manufacturer was responsible for designing the reinforcement that included length of the repair and the required thickness. Specific details on the composite repair systems are not included; however, the following types of composite repair systems participated in the current study.

- E-glass fibers in an epoxy matrix (2)
- E-glass fibers in a water-activated urethane matrix (2)
- Carbon fibers in an epoxy matrix (2)
- Carbon fibers in a water-activated urethane matrix (1)
- Pre-cured E-glass fiber wrap (1)

Once all of the composite repair systems were installed, strain gages were installed on the outside surface of three of the six repair sleeves on each 28-ft long test sample (i.e. one plain dent, one girth weld, and one ERW seam test sample).

TESTING RESULTS

The primary focus of the current study was to evaluate the level of reinforcement provided by composite materials in repairing dented pipelines. The most basic method of assessment is to compare how many cycles to failure occurred for each respective dent type and repair system. Additional insights are gained in evaluating the strain gages that measured strains in the dented regions of the pipe. Table 1 provides that dent depth data for the unrepaired dents. Note that a significant level of rerounding occurs. What was initially a dent depth equal to 15% of the pipe's outside diameter is reduced to something on the order of 5%. The sections that follow provide details on the measured cycles to failure and the strain gage data that were captured for the 6 unrepaired dents and the 42 dents repaired using 7 different composite repair systems.

Pressure Cycle Fatigue Data

All dented test samples were fatigue tested at a pressure range equal to 72% SMYS. As failures occurred, the failed pipe sections were removed and the remaining pipe was welded back together so that pressure cycling could continue. Table 2 provides a summary of all fatigue test results, while Figure 5 provides a graphical representation of the data listed in Table 2. The last column in Table 2 includes an average for all six dents associated with each repair systems, as well as the unrepaired dent set. Although the average value does not permit a direct comparison of test results for specific repair system/dent type combinations, it is a useful value for comparing the overall performance of the different repair systems relative to the unrepaired dents. The following general observations are made in reviewing the pressure cycle data.

- The average cycles to failure for the unrepaired dent samples were 10,957 cycles. The target number of *cycles to failure* for the unrepaired dents was 10,000 cycles.
- Two of the eight systems had 250,000 cycles survived no failures in any of their repaired dents. These two systems included a carbon/epoxy system and a pre-cured E-glass system.

Strain Gage Data

An extensive array of strain gage data was collected in the course of the current test program. A total of 24 dents were fitted with one bi-axial strain gage rosette that measured hoop and axial strains in the steel beneath the repairs. An additional 8 strain gages were used to monitor the nominal hoop and axial strains in the pipe during pressure cycling. As discussed previously in the *Test Methods* section of this paper, data were collected at start-up, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000 cycles or until failure assuming that the strain gages survived. Data were collected at a rate of one scan per second with typical cycle periods being on the order of 10 seconds.

There were two primary objectives in monitoring the strain beneath the composite repairs. The first was to quantify the level of reinforcement provided by the composite material. It is expected that as the composite material is engaged that it reduced strain in the section of pipe around which it is wrapped. Prior research has shown that the key to increasing the fatigue life of dents is to reduce the amount of flexure that takes place in the dented region of the pipe. The second objective was to monitor that the strain in the dented region as a function of cycle count and determine if this value changed over time.

An extensive assessment on the recorded strain gage data is outside the scope of this discussion; however, a summary of results is presented in Table 3. Provided in this table are the strain gage readings measured on the plain dents for each of the 8 test samples (16 dents in all). Although there is not a direct correlation between the average fatigue life (as observed experimentally) and the strain range, there are several noteworthy trends observed in viewing the data in Table 3.

- In general, those dents having the lowest reported strain ranges have the longest recorded experimental fatigue lives. System D had an average hoop strain range of 346 microstrain with no reported failures.
- The average hoop strain range for the base pipe was 1,000 microstrain, a value consistent with 72% SMYS divided by the elastic modulus of steel being 30 Msi (ε_{hoop} = 0.72 * 42,000 psi / 30 Msi = 1,008 microstrain). As observed 4 of the 7 repair systems had strain ranges of this magnitude or less (C, D, G, and H); these systems also recorded the highest average cycles to failure.
- The strain gages placed on the unrepaired dents recorded large strain ranges (4,678 $\mu\varepsilon$). When using the DOE-B mean curve (refer to equation provided in the *Discussion* section of this paper), the estimated cycles to failure is 2,670 cycles.

The average strain reported in Table 3 is a general measure of the level of reinforcement provided by the composite material. Although having low strain ranges does not guarantee that a particular system will always have the longest fatigue life, reduced strain is a good indicator that the repair system is reducing flexure of the dent. A case in point is that System A had relatively high recorded strains; however, the dents repaired using this system had an average fatigue life of 215,271 (second only to the two systems that achieved run-out).

DISCUSSION

The results of this program confirm that in addition to reinforcing corrosion damage in pipelines, composite materials are also well-suited to reinforce dents. In this capacity composite materials are effective because they are able to reduce stresses in the reinforced pipeline in the steel at the dented location. When plain dents have failed it has typically been due to cyclic pressures so that when composite materials are installed they increase the local stiffness of the dented region and reduce the alternating strains.

Although not specifically included in this paper, the thicknesses of the composite repairs were measured before testing. The average system thicknesses ranged from 0.175 inches (4.4 mm) to 0.671 inches (17 mm). The stiffness of the composite is the product of modulus and thickness. Contrary to what might be expected, there was not a direct correlation between stiffness and cycles to failure. Therefore, one can conclude that in addition to the stiffness of the fiber and matrix, the load transfer material (i.e. filler material) plays a significant role in the ability of the repair systems to reinforce the dented pipes. The importance of this observation cannot be overstated. This trend has also been observed when considering the repair of extreme corrosion depths (i.e. 75% of the nominal wall thickness).

Provided in Table 2 is a listing of stress amplification factors (SAFs) that were calculated for each of the repaired dents as well as the unrepaired data set. As observed, the maximum SAFs are those associated with the unrepaired dents (i.e. 3.76 for the unrepaired dent in an ERW seam, UR-ERW-1), while the minimum SAFs are those associated with the two repair systems that achieved run-out at 250,000 cycles (i.e. SAFs of 1.49 for Systems C and D).

- Calculate $\Delta\sigma$ using the known experimental cycles to failure, N, using the DOE-B mean curve [3] shown below. The DOE-B mean curve should not be used for design purposes; however, it is useful for estimating the remaining life of dented structures. See discussion below for recommended design curves.

$$N = 2.343E15 \cdot \left[\frac{\Delta\sigma}{0.145} \right]^{-4} \quad (1)$$

- Calculate nominal pressure hoop stress range ($\Delta\sigma_{hoop}$) based on ΔP
- Calculate the stress amplification factor using the following relation: SAF = $\Delta\sigma / \Delta\sigma_{hoop}$
- The SAF can be used to predict remaining life for repaired dents when the pipeline's pressure history is known. To calculate remaining life the SAF is multiplied by the nominal hoop stress to calculate stress range. This value is then used as input into an S-N fatigue curve to calculate the design life, N_{design}. Finally, the remaining service life in years for a given pipeline is determined by dividing N_{design} by the annual number of pressure cycles at a given pressure range.

Selecting an appropriate fatigue design curve is important. As discussed previously, the DOE-B mean curve is not to be used for estimating remaining life, although the DOE-B design curve is an option. Also, for relatively severe dents, the author has used the API X' curve from API RP 2A [4]. Provided below are three sets of equations that compare the DOE-B mean, DOE-B design, and the API

X' design curves. The elastic stress range, $\Delta\sigma$, of 140,340 psi used in these equations corresponds to the measured strain of 4,678 εμ (elastic stress of 140,340 psi) for the unrepaired plain dent that failed after 7,018 cycles.

DOE-B Mean Curve

$N = 2.343 \times 10^{15} (\Delta\sigma / 145)^{-4} =$

2.343×10^{15} (140,340 psi / 145)$^{-4}$ = **2,670 cycles**

DOE-B Design Curve (mean minus two standard deviations)

$N = 1.01 \times 10^{15} (\Delta\sigma / 145)^{-4} =$

1.01×10^{15} (140,340 psi / 145)$^{-4}$ = **1,151 cycles**

API X' Curve

$N = 2 \times 10^{6} (\Delta\sigma / 11{,}400 \text{ psi})^{-3.74} =$

2×10^{6} (140,340 psi / 11,400 psi)$^{-3.74}$ = **167 cycles**

If one compares the above two design curves, the fatigue design margins relative to the actual experimental cycles to failure for the DOE-B and API X' design curves are 6.1 and 42.0, respectively. The design curves in the ASME Boiler & Pressure Vessel Curve impose a design margin of 20 on cycles to failure; therefore, one could conclude that the API X' is possibly too conservative, while the DOE-B design curve might not conservative enough. The selection of design curves is a function of each operator's risk tolerance.

In terms of remaining life, the 250,000 pressure cycles achieved by Systems C and D corresponds to a remaining life of 6,250 years considering a safety factor of 20 on *cycles to failure* and an *aggressive pressure cycle condition* for a gas transmission pipeline (20 cycles per year at a pressure range of 72% SMYS) as defined by Kiefner [7]. Correspondingly, using this same approach the average cycles to failure for the unrepaired dents is 27 years. The difference between these remaining years of service is a factor of more than 230 times. For liquid transmission pipelines, which typically experience a larger number of pressure cycles than gas transmission lines, the above estimated remaining years of service will be less.

One of the challenges in evaluating the extensive database of test results associated with composite repair systems is determining the most effective means for direct comparison. This challenge is even present in the program presented in this paper that involved evaluating 54 different unrepaired and repaired dent defects. However, the development of SAFs permits both pipeline operators and composite repair manufacturer suppliers with a direct means for determining the remaining life of dents and the associated extension of fatigue life when composite materials are used based on actual test data. From a design standpoint it is the authors' opinion that when using current composite technology the thickness of the composite should never be less than the thickness of the pipe when repairing dents.

It should be noted that the current test program utilized a specific set of dent types, pipe geometry and grade, and composite repairs (i.e. materials and thicknesses). However, the findings of this study should not be considered as limiting. For several composite repair systems to have demonstrated the ability to increase the fatigue life of unrepaired dents by a factor or more than 25 is a critically important observation. At the present time what is absent in industry is a cohesive, uniform set of design guidelines for repairing dents using composite materials; however, programs such as the one reported herein provide industry with the foundational data necessary to develop a guidelines. In the absence of definitive guidelines, qualification of composite repairs by performance testing is the best available option for industry. This is further supported by the fact that the nature of the filler is of critical importance. As there are no methods to identify what will and what will not work, all systems should be tested to validate performance.

One final comment concerns the failure modes of plain dents and dents combined with girth and seam welds. The primary focus of this study has been on evaluating the performance of dents subjected to cyclic pressure service. Although burst failures can happen to these types of anomalies, these types of dents most often fail in fatigue [6]. When burst failures do occur, more often than not there are additional extenuating circumstances that contribute to the failures such as metal loss (i.e. corrosion), pre-existing flaws or cracks, and external loads.

CONCLUSIONS

Since the 1990s composite materials have been used to repair corrosion in high pressure transmission pipelines. The use of this advanced technology has gained wide acceptance throughout industry and over the past several years multiple Joint Industry Programs have been sponsored by pipeline operators and composite manufacturers to both evaluate their capabilities and demonstrate the range of their ability to restore integrity to damaged pipelines. The information presented in this paper has detailed the results from a test program aimed at evaluating the ability of composite materials to reinforce damaged pipelines including plain dents, dents in seam welds, and dents in girth welds subjected to cyclic pressures.

The results clearly demonstrate that when properly designed and installed based on manufacturer-defined specifications, composite materials can significantly increase the fatigue life of dented pipelines. The average cycles to failure for six unrepaired dent defects was 10,957 cycles, while 2 of the 7 composite systems had no fatigue failures even after 250,000 pressure cycles had been applied. As noted previously, this extreme pressure condition corresponds to a remaining life of 6,250 years considering a safety factor of 20 on *cycles to failure* and an *aggressive pressure cycle condition* for a gas transmission pipeline (20 cycles per year at a pressure range of 72% SMYS). It is expected that future activities will use information presented in this paper as the foundation for developing guidelines that can be used by other manufacturers and operators in designing composite repair systems for the repair of dented pipelines.

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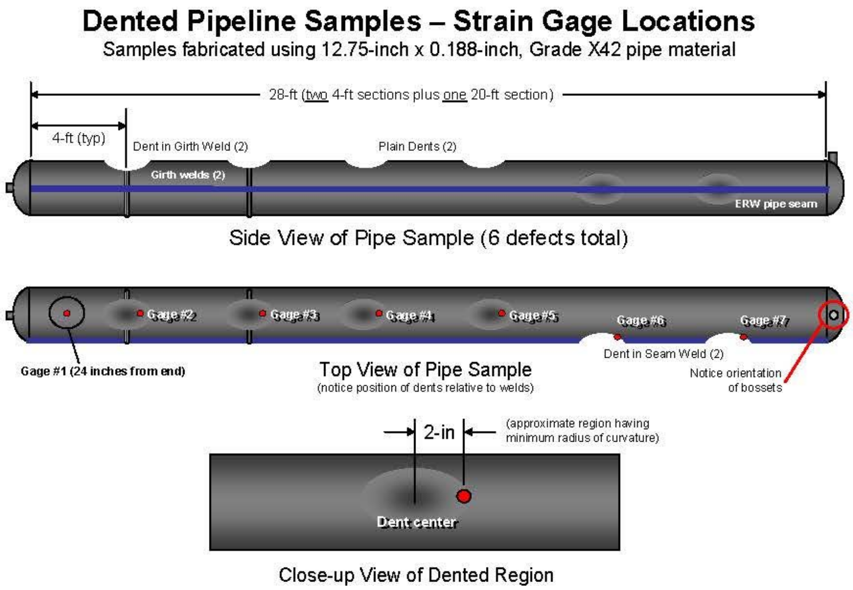


Figure 1 – Layout for pipe samples with 6 defects per sample
(the off-axis orientation of the dents interacting with the seam weld alleviates the need for an additional girth weld)

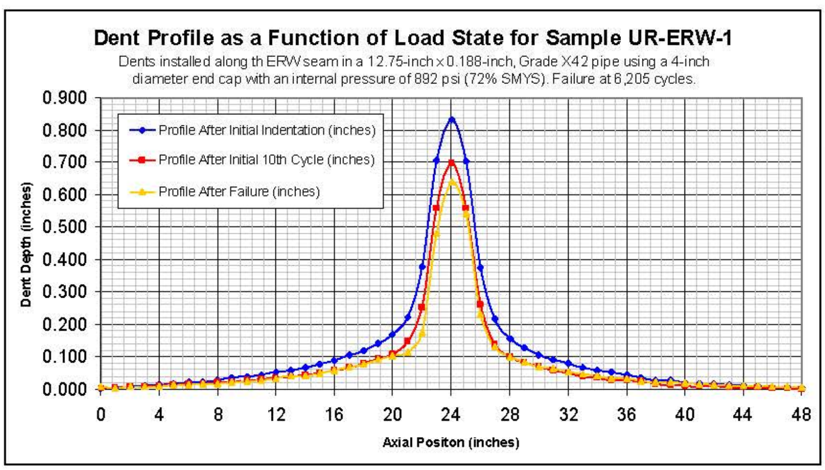


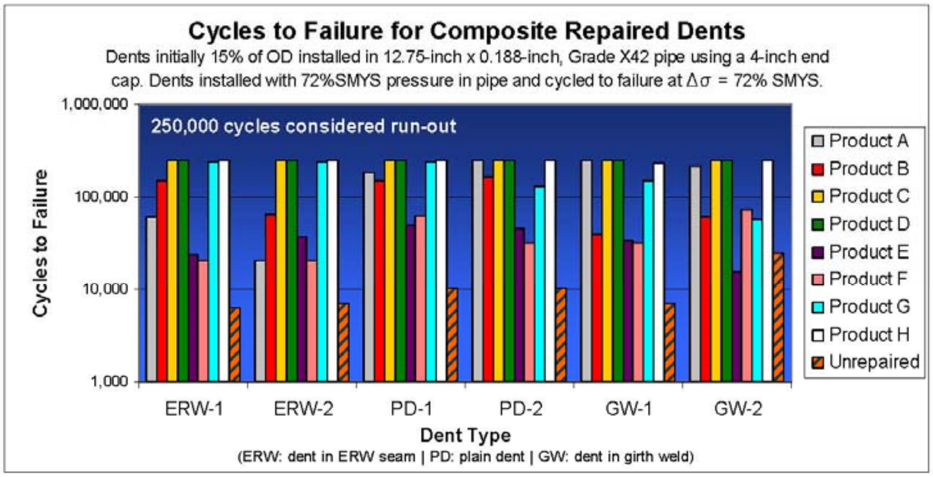
Figure 2 – Dent profile for unrepaired 15% dent in ERW seam
(residual initial dent depth of 6.54% with final post-failure dent depth of 5.01%)

5

Figure 3 – Close-up view on indenter on girth weld

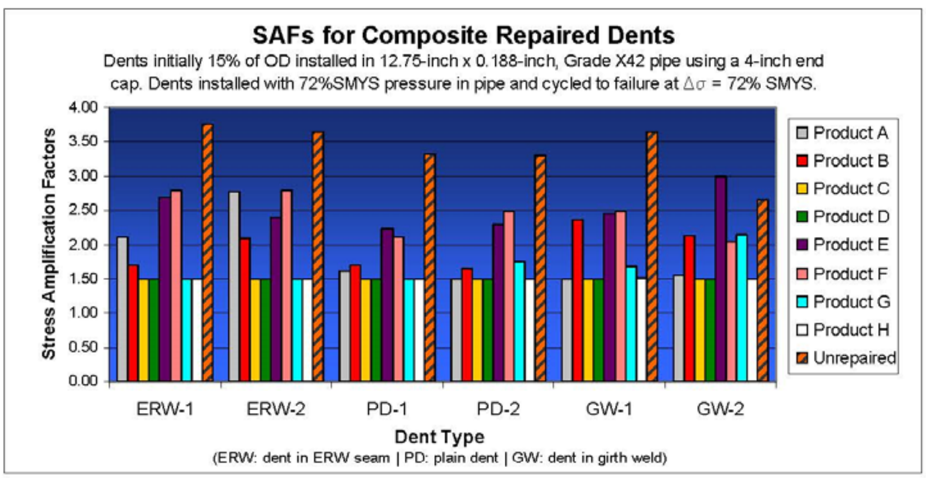
Figure 4 – Remaining dent profile after the application of 10 pressure cycles

6



One system was pressure cycled to 358,470 cycles when the ERW seam failed.

Figure 5 – Pressure cycle results for all dented test samples



Calculating Stress Amplification Factors (SAFs)

1. Calculate $\Delta\sigma$ using known cycles to failure, N
2. Calculate nominal pressure hoop stress range ($\Delta\sigma_{hoop}$) based on ΔP
3. SAF = $\Delta\sigma / \Delta\sigma_{hoop}$
4. The SAF can be used to predict remaining life for repaired dents when the pipeline's pressure history is known.

DOE B-curve

$$N = 2.343 \times 10^{15} \bullet \left[\frac{\Delta\sigma}{0.145}\right]^{-4}$$

$\Delta\sigma$ in units of ksi

Figure 6 – Calculated Stress Amplification Factors (SAFs) for dented test samples

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Table 1 – Summary of Depths from Unrestrained Dents
(initial dents depths equal to 15% of pipes outside diameter)

Dent Type	Number	Profile After Initial Indentation (inches)		Profile After 10 Pressure Cycles (inches)		Final Profile After Fatigue Failure (inches)	
		Dent Depth (inches)	Dent Depth (%)	Dent Depth (inches)	Dent Depth (%)	Dent Depth (inches)	Dent Depth (%)
Plain	UR-PD-1	0.775	6.08%	0.601	4.71%	N/A	N/A
	UR-PD-2	0.765	6.00%	0.616	4.83%	N/A	N/A
ERW	UR-ERW-1	0.834	6.54%	0.699	5.48%	0.639	5.01%
	UR-ERW-2	0.895	7.02%	0.725	5.69%	0.638	5.00%
Girth Weld	UR-GW-1	0.699	5.48%	0.554	4.34%	N/A	N/A
	UR-GW-2	0.657	5.15%	0.560	4.39%	N/A	N/A

Table 2 – Summary of Fatigue Data and Calculated SAFs

Product	Sample	# of Cycles	Modified N	Δσ (ksi)	SAF	AVG
A	A-ERW-1	61,757	61,757	64.0	2.12	162,308
	A-ERW-2	20,881	20,881	83.9	2.78	
	A-PD-1	181,857	181,857	48.9	1.62	
	A-PD-2	248,684	248,684	45.2	1.49	
	A-GW-1	309,934	250,000	45.1	1.49	
	A-GW-2	210,671	210,671	47.1	1.56	
B	B-ERW-1	148,892	148,892	51.4	1.70	104,581
	B-ERW-2	63,979	63,979	63.4	2.10	
	B-PD-1	148,892	148,892	51.4	1.70	
	B-PD-2	165,809	165,809	50.0	1.65	
	B-GW-1	39,655	39,655	71.5	2.36	
	B-GW-2	60,260	60,260	64.4	2.13	
C	C-ERW-1	305,353	250,000	45.1	1.49	250,000
	C-ERW-2	305,353	250,000	45.1	1.49	
	C-PD-1	305,353	250,000	45.1	1.49	
	C-PD-2	305,353	250,000	45.1	1.49	
	C-GW-1	305,353	250,000	45.1	1.49	
	C-GW-2	305,353	250,000	45.1	1.49	
D	D-ERW-1	261,742	250,000	45.1	1.49	250,000
	D-ERW-2	261,742	250,000	45.1	1.49	
	D-PD-1	261,742	250,000	45.1	1.49	
	D-PD-2	261,742	250,000	45.1	1.49	
	D-GW-1	261,742	250,000	45.1	1.49	
	D-GW-2	261,742	250,000	45.1	1.49	
E	E-ERW-1	23,890	23,890	81.1	2.68	34,254
	E-ERW-2	37,011	37,011	72.7	2.41	
	E-PD-1	50,334	50,334	67.4	2.23	
	E-PD-2	44,987	44,987	69.3	2.29	
	E-GW-1	33,900	33,900	74.3	2.46	
	E-GW-2	15,400	15,400	90.6	2.99	
F	F-ERW-1	20,511	20,511	84.3	2.79	40,017
	F-ERW-2	20,445	20,445	84.4	2.79	
	F-PD-1	62,324	62,324	63.8	2.11	
	F-PD-2	32,273	32,273	75.3	2.49	
	F-GW-1	32,366	32,366	75.2	2.49	
	F-GW-2	72,183	72,183	61.5	2.04	
G	G-ERW-1	241,864	241,864	45.5	1.50	177,657
	G-ERW-2	241,864	241,864	45.5	1.50	
	G-PD-1	241,864	241,864	45.5	1.50	
	G-PD-2	131,040	131,040	53.0	1.75	
	G-GW-1	151,603	151,603	51.1	1.69	
	G-GW-2	57,704	57,704	65.1	2.15	
H	H-ERW-1	356,446	250,000	45.1	1.49	247,075
	H-ERW-2	358,470	250,000	45.1	1.49	
	H-PD-1	358,470	250,000	45.1	1.49	
	H-PD-2	358,446	250,000	45.1	1.49	
	H-GW-1	232,449	232,449	45.9	1.52	
	H-GW-1	313,747	250,000	45.1	1.49	
UR	UR-ERW-1	6,205	6,205	113.7	3.76	10,957
	UR-ERW-2	7,018	7,018	110.2	3.64	
	UR-PD-1	10,163	10,163	100.5	3.32	
	UR-PD-2	10,334	10,334	100.1	3.31	
	UR-GW-1	7,023	7,023	110.2	3.64	
	UR-GW-2	24,996	24,996	80.2	2.65	

Table 3 – Summary of Strain Gages Results for Unreinforced/Reinforced Plain Dents
(strain gages located beneath composite repairs in dented region of steel pipe)

Product	Hoop Strain (microstrain)			Plain Dent Experimental $N_{average}$	DOE-B mean (calculated cycles to failure)
	Plain Dent #1	Plain Dent #2	Average		
A	1,753	1,990	1,872	215,271	104,232
B	1,748	1,894	1,821	157,351	116,284
C	950	1,148	1,049	250,000	1,055,984
D	317	374	346	250,000	89,736,075
E	1,645	1,455	1,550	47,661	221,530
F	1,544	1,814	1,679	47,299	160,900
G	901	1,018	960	186,452	1,508,618
H	245	275	260	250,000	279,811,711
Unrepaired	N/A	4,678	4,678	10,249	2,670

Notes:
1. The unit of measure typically used for strain gages is *microstrain* (με), where 10,000 microstrain equals 1 percent strain.
2. The average hoop strain range for the base pipe was 1,000 microstrain, a value consistent with 72% SMYS divided by the elastic modulus of steel being 30 Msi (ε_{hoop} = 0.72 * 42,000 psi / 30 Msi = 1,008 microstrain).
3. The $N_{average}$ value is the average number of experimental cycles to failure for each respective plain dent data set (fatigue data for plain dents presented in Table 2).
4. The last column, denoted as DOE-B mean, is the calculated cycles to failure using the DOE-B mean curve (shown below) and the average measured hoop strain. Hoop stress in unit of "ksi" is calculated by multiplying hoop strain by elastic modulus (30 Msi) and then dividing by 1,000 psi / ksi. For example, System had an average recorded hoop strain of 960 με; the corresponding stress range is 960 με * 30 Msi / 1,000 = 28.8 ksi.

Appendix F: Reinforcement of Planar Defects Using Composite Materials

Alexander, C., and Scrivner, R. (Stress Engineering Services, Inc.).
Rizk, T., Wang, T., and Clayton, R. (Boardwalk Pipeline Partners, LP)

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REINFORCEMENT OF PLANAR DEFECTS IN LOW-FREQUENCY ERW LONG SEAMS USING COMPOSITE REINFORCING MATERIALS

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas

Tony Rizk
Boardwalk Pipeline Partners, LP
Houston, Texas

Henry Wang
Boardwalk Pipeline Partners, LP
Houston, Texas

Rodney Clayton
Boardwalk Pipeline Partners, LP
Houston, Texas

Ron Scrivner
Stress Engineering Services, Inc.
Houston, Texas

ABSTRACT

A comprehensive study was conducted to investigate the reinforcement of LF-ERW flaws located in a 16-inch x 0.312-inch (406-mm x 7.93-mm), w.t. Grade X52 ethylene pipeline. The study was prompted by an in-service leak that was discovered in an LF-ERW seam during routine maintenance activities. The investigation was subsequently expanded as a result of the discovery of several additional leaks. An initial failure analysis of the leak location was conducted followed by broader material testing, full-scale testing, and metallurgical analysis of the remaining pipe. The use of composite repair systems as a feasible method of LF-ERW seam reinforcement was also examined. As part of this study, testing was also conducted on 8.625-inch x 0.250-inch. (219-mm x 6.35-mm) pipe material having LF-ERW seams.

Test results documented the potential for composite repair systems to provide reinforcement to LF-ERW flaws and crack-like defects. Distinct contrasts were observed between the performance of samples with unreinforced and reinforced notches subjected to cyclic pressure and burst tests. Reinforced samples exhibited improvements in pressure cycle life and significantly increased burst pressure capacities as compared to unreinforced samples. The results of this program demonstrate that, when properly designed and installed, composite materials are an effective means for reinforcing LF-ERW long seam weld flaws and other planar defects. The composite repairs served to ensure that cracks neither form nor propagate during aggressive pressure cycling and burst testing. It should be noted that the testing program was specific to the operating and material conditions associated with a particular ethylene pipeline that is the subject of this paper.

INTRODUCTION

A study was conducted to investigate the use of composite repair systems to reinforce original manufacturing defects and cracks in LF-ERW seams (LF-ERW: low frequency electrical resistance weld). Full-scale testing was performed on 8.625-inch x 0.250-inch (219-mm x 6.35-mm), Grade X46 and 16-inch x 0.312-inch (406-mm x 7.93-mm), Grade X52 LF-ERW pipe materials with notches installed via electrical discharge machining (EDM) in the long seam welds of the pipe samples to simulate crack-like defects. This study was prompted by the discovery of a leak in a 16-inch (400-mm) ethylene pipeline. The 8-inch (200-mm) samples were taken from a previous project and were included in this study because they contained LF-ERW seams and were the most efficient approach for supplementing the limited amount of 16-inch (400-mm) pipe material available for this particular study.

To investigate the use of composite repairs as a feasible reinforcement technique, a series of pressure tests that included pressure cycling and burst tests were conducted on reinforced and unreinforced pipe samples. The tested composite repairs included systems manufactured by Milliken-Pipe Wrap and Western Specialties. Milliken-Pipe Wrap used its Atlas carbon-epoxy repair system, while Western Specialties installed its CompositSleeve hybrid steel-composite (water-activated urethane) repair system. The unreinforced samples were tested as reference cases and underwent both cyclic pressure and burst testing. Installation of the repair systems was performed by the manufacturers on 16-inch (400-mm) and 8-inch (200-mm) pipe samples. The 16-inch (400-mm) and 8-inch (200-mm) samples were cut to lengths of 8 ft. (2.44 m) and 4 ft. (1.22 m), respectively.

This paper includes a *Test Methods* section, which provides details on the test samples and testing configuration, while the *Test Results* includes data from the pressure cycle and burst tests. The *Conclusions* section provides several closing comments relating the study's findings to the actual operation of the pipeline.

TEST METHODS

The sections that follow provide information on the test samples used in this test program, along with details on specific aspects of the test program and design details on the composite reinforcing technologies.

Test Sample Details

To simulate the reinforcement of crack-like defects, EDM notches were installed in the 8-inch (200-mm) and 16-inch (400-mm) pipe samples. These notches were located such that they interacted with the pipe's ERW weld seam (bond line). Schematics showing details of the EDM notches, including location and geometry, are provided in Figure 1. Photographs of the EDM notches are shown in Figure 2. Prior to installation of the notches, in-depth inspection efforts were conducted to ensure that the notches were placed in the bond line of the long seam welds. To generate microcracking at the base of the EDM notches, pressure cycles are typically applied to test samples prior to actual testing (including composite installation); however, after multiple failures occurred in less than 100 cycles it was concluded that even without pre-cycling the flaws associated with the LF-ERW seams were adequate for testing.

It can be seen in these schematics and photographs shown in Figure 1 and Figure 2 that three (3) EDM notches were installed per sample. This was done to increase the statistical significance of each sample. The failed samples were examined after testing to ensure that the EDM notches intersected the LF-ERW seam. The samples that did not fail were sectioned through the notch and a metallographic examination was performed to ensure that the notches corresponded with the LF-ERW seam.

Confirmation of the interaction between the EDM notches and the LF-ERW seam line for the 16-inch (400-mm) Milliken-Pipe Wrap reinforced sample is shown in Figure 3; demonstrating that the EDM notch intersected the bond line. The photographs shown are post-test sections taken through the EDM notches (after all phases of pressure cycle and burst testing were completed). This particular ethylene pipeline system does not experience cyclic pressure loading, so there was no reason to perform aggressive pressure cycling or address issues related to fatigue loading.

Test Overview

Both cyclic pressure and burst testing were performed on pipes that had been repaired using the two (2) repair systems. Pressure testing was also conducted on samples with EDM notches that had not been reinforced as a baseline case. Details on the installation and test methods used for each case are provided below.

Installation of Reinforcement Systems

The repair systems were installed at Stress Engineering Services Inc.'s (SES) test facility located in Houston, Texas. The composite repair installations were performed by each respective manufacturer. Prior to installation of the repair systems, the pipe samples were sandblasted to a near-white metal (NACE 2). A photograph of the Atlas system prior to testing is shown in Figure 4. The Atlas system uses a carbon-fiber fabric with a field-impregnated epoxy resin matrix. Photographs showing installation of the ComposiSleeve system are given in Figure 5 and Figure 6. This particular system employs two half-shells that are adhered to the pipe using a high-strength acrylic and overwrapped with a water-activated pre-impregnated E-glass/urethane composite system.

Cyclic Pressure Testing

Cyclic pressure testing was performed prior to burst testing for all samples. The intent in cycling was to provide an opportunity for crack growth at the base of the EDM notch. The desired pressure range for all samples was 10% to 72% of the Specified Minimum Yield Strength (SMYS). For the 8-inch (200-mm) samples, this corresponded to pressures ranging from 267 psi to 1,920 psi (1.84 MPa to 13.24 MPa), while the pressures for the 16-inch (400-mm) samples were 202 psi to 1,460 psi (1.39 MPa to 10.07 MPa). The internal pressure range was monitored using pressure transducers that were continuously recorded. Each sample type (i.e., 8-inch (200-mm) vs. 16-inch (400-mm), repaired vs. unrepaired) had a target number of pressure cycles that was specified prior to the start of testing. Table 1 provides the target number of cycles for each sample type. This particular line does not see a significant number of pressure cycles to pressure conditions were selected in testing to reflect this condition (150 and 350 cycles for the 8-inch (200-mm) and 16-inch (400-mm) pipe, respectively); however, for conservatism the target number of cycles for each size was increased by a factor of 10 for the reinforced test samples. It should be noticed that the quality of the seams in the 8-inch (200-mm) pipe were so poor that several of the test samples failed in the pressure cycle, so that 150 cycles was never reached.

During pressure testing, strain gages and clip gages were used to monitor stresses in the pipes and crack growth in the EDM notches, respectively. Clip gages specifically measured notch growth during cycling and were only installed on the unreinforced samples. Strain gages were able to be installed both on unreinforced and reinforced samples (i.e., the strain gages could be installed beneath some of the repairs). Photographs showing clip gages installed on an unrepaired sample are given in Figure 7. A strain gage installed over an EDM notch is shown in Figure 8; the gage is shown as installed with the ComposiSleeve repair where washers were installed to prevent the gages from being crushed during installation of the steel half-shells. It should be noted that the wire mesh shown in Figure 8 is specific to ComposiSleeve repairs.

Pressure data were provided for the pipeline for approximately 390 days. A rainflow count of the data was completed to assess the number of cycles experienced by this particular pipeline. Plotted in Figure 10 is a histogram showing the results for the pressure data. As observed, this particular pipeline experiences minimal pressure cycling. Using Miner's Rule to develop a single equivalent cycle number for a pressure range of 202–1,460 psi (1.39 MPa to 10.07 MPa) (10% to 72% SMYS) for the given data, the result is 0.52 cycles per year. Using this relation, the 3,500 cycles applied to the 16-inch (400-mm) test samples corresponds to 6,736 years of service (i.e. 3,500 cycles / 0.52 cycles per year). From these data one can conclude that this particular pipeline system experiences minimal pressure cycling.

Burst Testing

Following pressure cycling, the surviving samples were burst tested in a covered pit with bolted shielding. A pressure transducer was used to monitor the internal pressure. Strain gages used during pressure cycling were continuously recorded during burst testing.

Burst testing consisted of an initial pressurization to 90% SMYS to simulate hydrotest conditions as required by the regulators for this pipeline system, which was held for 30 minutes. This corresponded to 2,400 psi (16.55 MPa) for the 8-inch (200-mm) samples and 1,825 psi (12.58 MPa) for the 16-inch (400-mm) samples. Following the hold period, the internal pressure was reduced to zero prior to pressurizing the sample to failure. Values for pressures equal to 72% SMYS, 90% SMYS, and 100% SMYS for both 8-inch (200-mm) and 16-inch (400-mm) samples are provided in Table 2.

Composite Repair Design

A central objective of this program was quantifying performance of the tested composite repair systems. Because this program was the first of its kind in terms of reinforcing cracks in LF-ERW seams, the repair manufacturers recognized the importance of installing adequate amounts of material to minimize crack initiation and propagation. Each manufacturer was responsible for the design of their system, although SES provided some assistance in terms of the amount of material that would be required to minimize strains in the reinforced steel.

The installation procedures employed by both manufacturers were similar to those used for repairing other pipeline anomalies such as corrosion and dents. The thickness of the ComposiSleeve system was similar to what would be expected for a typical corrosion repair; however, the thickness of the Atlas carbon system was thicker than what might be expected for a typical corrosion repair. It is possible that both systems might have been overdesigned (i.e. greater thickness than actually required); however, the solid performance of both systems as demonstrated in testing illustrated the benefits in having thick repairs. At the present time there is no guidance available from the composite repair standards (ASME PCC-2-2015 and ISO 24817), so both manufacturers designed repairs outside conventional designs typically used for the reinforcement of corrosion defects.

Once testing was completed with satisfactory results, all parties participating in this study recognized that follow-on work would likely be conducted to optimize the composite designs by making adjustments to the thickness of the repairs. Provided below are the measured composite repair thicknesses.

- Western Specialties ComposiSleeve
    - 8-inch repairs: 0.25-inch steel | 0.201-inch composite (200-mm repairs:6.35-mm steel | 5.1-mm composite)
    - 16-inch repairs: 0.25-inch steel | 0.220-inch composite (400-mm repairs: 6.35-mm steel | 5.6-mm composite)
- Milliken-Pipe Wrap Atlas
    - 8-inch repairs 0.631-inch composite (200-mm repairs 16-mm composite)
    - 16-inch repairs 0.701-inch composite (400-mm repairs 17.8-mm composite)

TEST RESULTS

This section of the paper provides the results from the test program described previously. Results are presented for both the cyclic pressure and burst testing phases of the program. It should be noted that strain gage results are only presented for the Atlas test samples as strain gage results associated with the ComposiSleeve system were unreliable as they were likely damaged during installation.

Cyclic Pressure Testing

Cyclic pressure testing resulted in all repaired samples achieving the designated 1,500 cycles and 3,500 cycles for 8-inch (200-mm) and 16-inch (400-mm) samples, respectively. Two (2) of the five (5) unreinforced test samples did not reach the target number of cycles during pressure cycling. Failure of these samples occurred during the initial pressure increase of the first cycle. Strain results for several of the samples that did reach the target number of cycles are provided in Figure 11. The strain ranges in these plots were taken from strain gages that were installed across EDM notches. Linear trend lines were added to this plot showing a general strain range increase with the unreinforced samples, while there appear to be minimal strain range changes on the composite material is installed.

In a similar round of tests, base pipe and notch strain data were recorded during pressure cycling of the 16-inch (400-mm) samples. A comparison between the 16-inch (400-mm) unreinforced and reinforced notch data through the first 500 cycles is shown in Figure 12. As observed, the Atlas carbon-epoxy composite system managed to maintain the strain range during pressure cycling to 700 $\mu\varepsilon$ though 500 cycles, while the unreinforced notch gages eventually failed after 350 cycles due to excessive crack growth. Trend lines are included for select data confirming this strain range pattern with increasing cycle number.

A summary of the cyclic pressure testing results can be found in Table 3. In this table, the pressure range and number of cycles completed are given for each of the samples tested. Additionally, details regarding the failure pressures of the two (2) samples that failed during the first pressure cycle are also provided.

Burst Pressure Testing

Burst testing was performed on all samples that reached the target number of cycles during cyclic testing. Comparisons of the results from pressure to failure tests are presented in Table 4; the burst pressures have been averaged for each of the sample groups and compared to the average failure pressure for the respective unreinforced sample set. Each of the reinforced sample sets exhibited an average burst pressure increase of at least 130% relative to the unreinforced samples of the same diameter. All samples, except for Unreinforced Sample #2, which failed at 2,105 psi (14.51 MPa) (79% SMYS), had burst pressures that exceeded 100% SMYS (2,667 psi (18.39 MPa) for the 8-inch (200-mm) pipe and 2,028 psi (13.98 MPa) for the 16-inch (400-mm) pipe).

Strain data were recorded for all of the burst tests. However, for brevity, only results for the Milliken-Pipe Wrap system used to reinforce an 8-inch (200-mm) pipe sample are presented (cf. Figure 13). As observed in this plot, the reinforced sample exhibited lower strain values at a given pressure than those measured in the unreinforced sample. This is shown as a shift to the left (i.e., increase in slope) in the curve plotting pressure versus hoop strain, which represents an increase in stiffness that is required for a repair system to reinforce pipeline anomalies.

A comment is made regarding the ability of the composite reinforcing systems to minimize—or in some cases mitigate—crack growth and propagation. The images provided in Figure 3 were taken after all pressure cycling and burst testing was complete on one of the Milliken-Pipe Wrap samples. These images show that not only was the EDM positioned in the ERW bond line, but that the Milliken-Pipe Wrap Atlas system prevented any growth of the EDM notch.

In addition to testing the anomalies associated with the EDM notches, planar defects removed from the actual pipeline were tested. The defects were identified via an in-line combination magnetic flux leakage tool; the two most significant anomalies found were selected for further composite reinforcement validation testing. Figure 14 includes two photographs showing these two anomalies after burst testing. As noted, both failed at pressures in excess of two times the Maximum Operating Pressure (MOP) of the line and the failure occurred outside the repairs. Shown in Figure 15 is a post flaw inspection of one of the reinforced samples where there appears to be no growth in the flaw during the pressure test.

CONCLUSIONS

The potential for composite repair systems to provide reinforcement to LF-ERW flaws and crack-like defects was demonstrated in this study. Distinct contrasts were observed between the performance of samples with unreinforced and reinforced EDM notches when subjected to cyclic pressure and burst tests. Reinforced samples exhibited improvements in pressure cycle life and significantly increased burst pressure capacities when compared to unreinforced samples. A direct comparison of these results showed that both of the tested reinforcement systems are likely to improve the performance of pipes with crack-like defects to some degree. The results indicate a consistency in performance of the Atlas system, which is crucial to demonstrate a quality repair. The ability of the wet wrap to conform to the outside surface of the pipe, while also providing reinforcement, was a key contributor to the success of this technology.

The results of this study demonstrated that, when properly designed and installed, composite materials are an effective means for reinforcing LF-ERW long seam welds and other planar defects to ensure that cracks neither form nor propagate during aggressive pressure cycling and burst testing. The results associated with this program are applicable to the 16-inch (400-mm) ethylene pipeline. The testing program was specific to the operating and material conditions associated with this particular ethylene pipeline.

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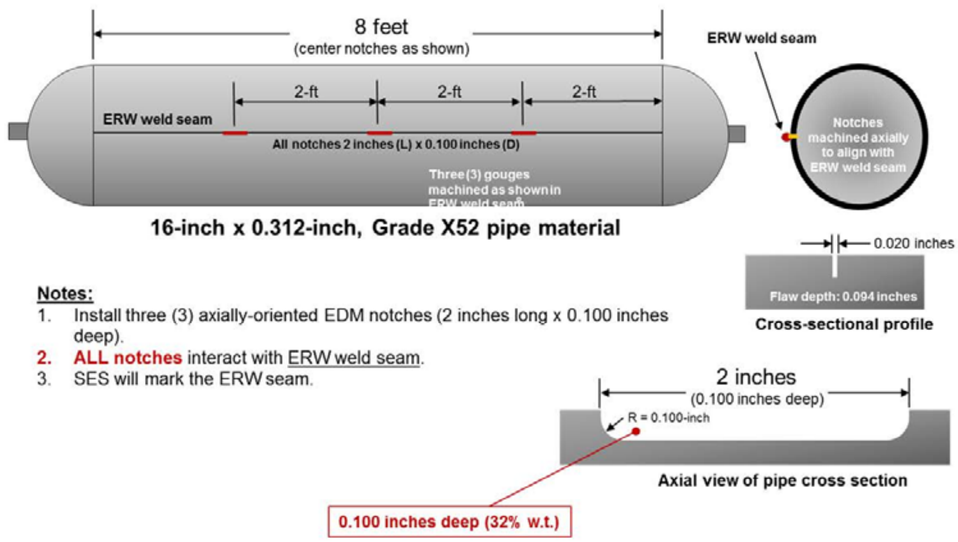

Figure 1: Schematic of 16-inch Pipe Samples with EDM Notches

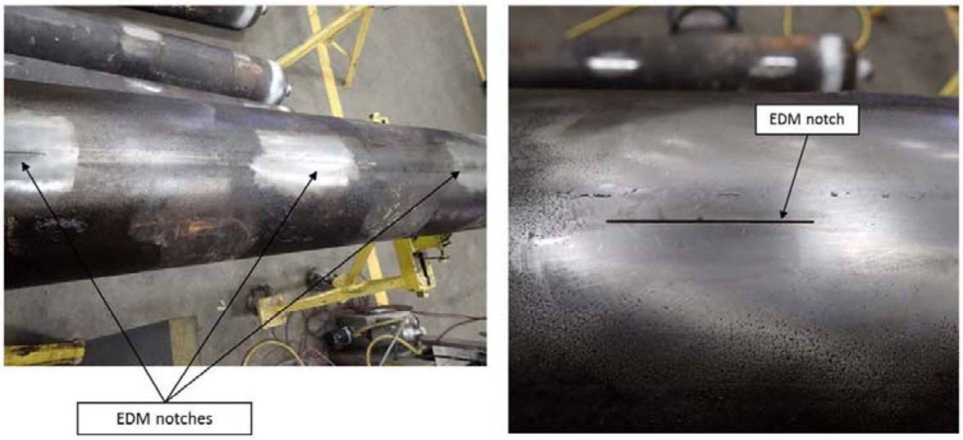

Figure 2: Photographs of EDM Notches

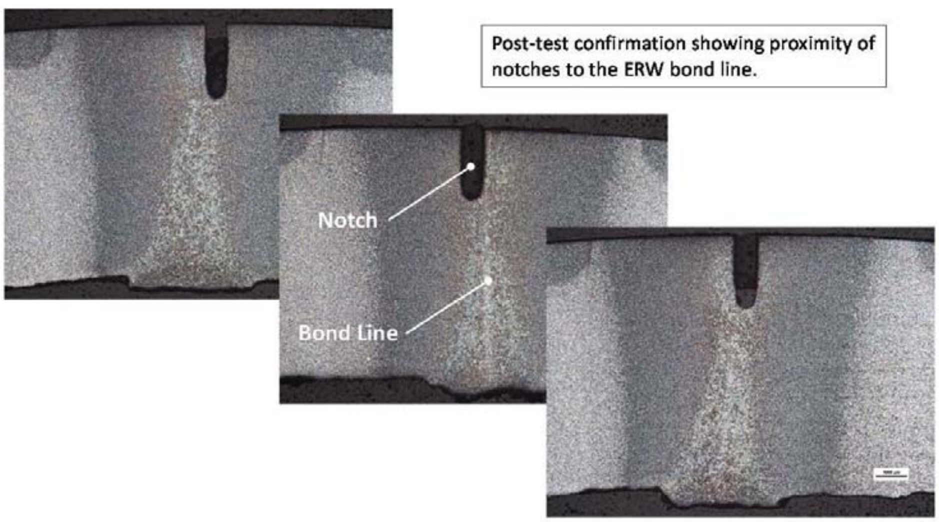

Figure 3: Sections of EDM Notches through LF-ERW Bond Lines of 16-inch pipe (Taken after burst testing from one of the Milliken-Pipe Wrap samples)

Figure 4: Milliken-Pipe Wrap Atlas System – as Repaired and Set up for Testing

Figure 5: Installation of the Western Specialties ComposiSleeve

Figure 6: Installation of the Western Specialties ComposiSleeve System

Figure 7: Photograph of Clip Gages on Unreinforced Samples

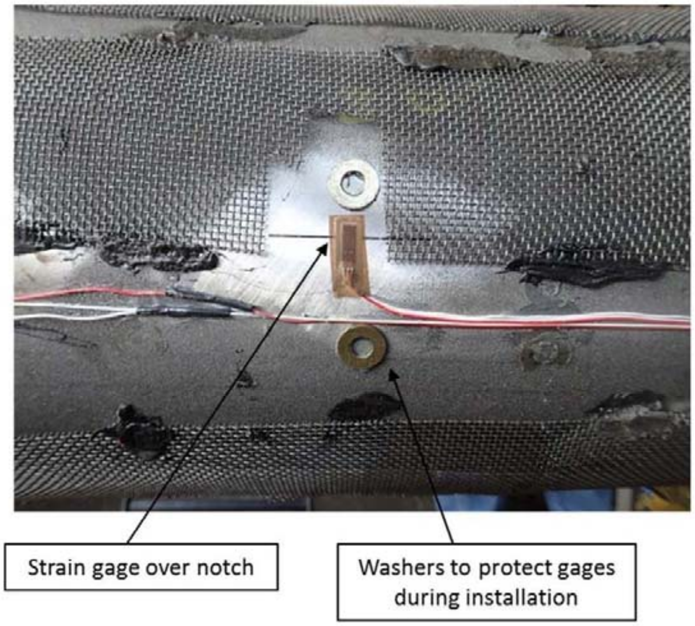

Figure 8: Photograph of Notch Strain Gage on ComposiSleeve Sample

Figure 9: Photograph of Pipe Samples Installed for Pressure Cycling

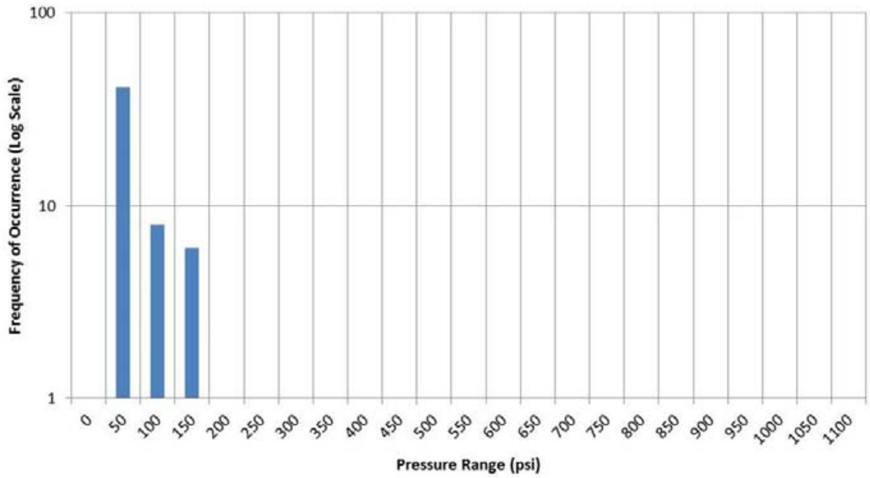

Figure 10: Histogram of Pressure Cycle Data (390 days of data collected)

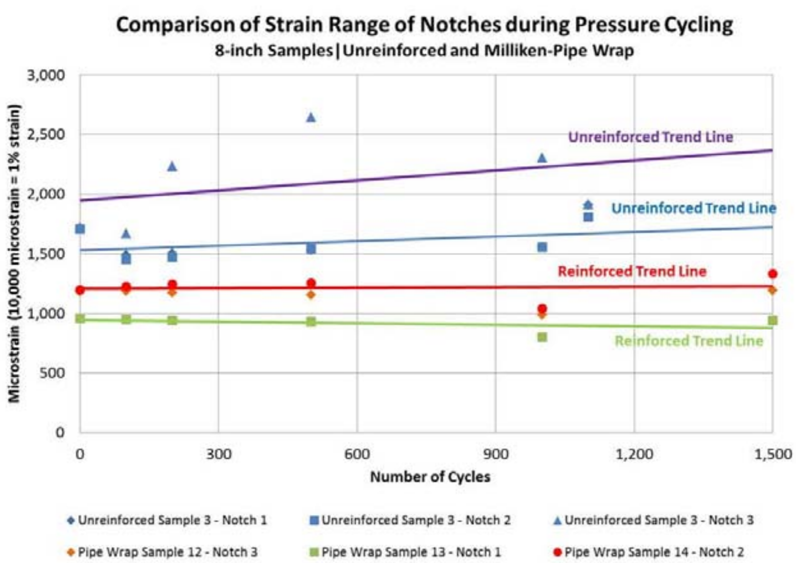

Figure 11: Notch Strain Range vs. Number of Cycles (selected 8-inch diameter samples)

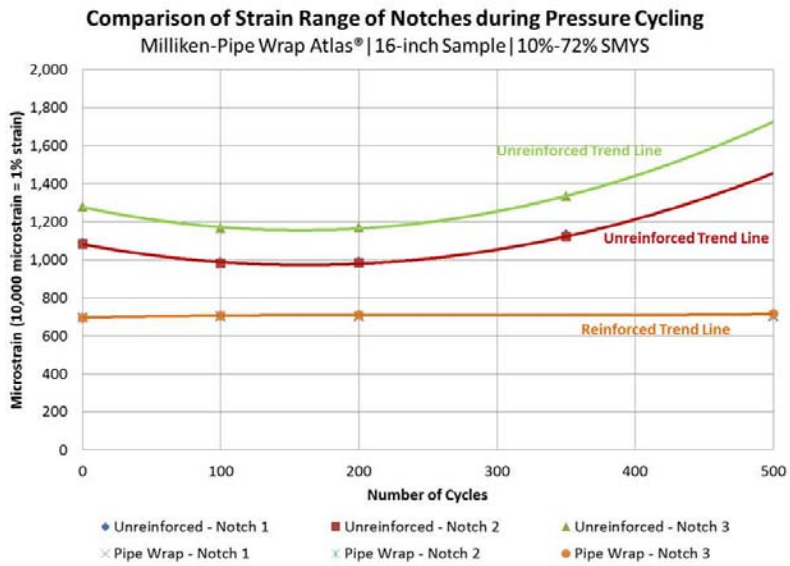

Figure 12: Notch Strain Range vs. Number of Cycles (selected 16-inch diameter samples)

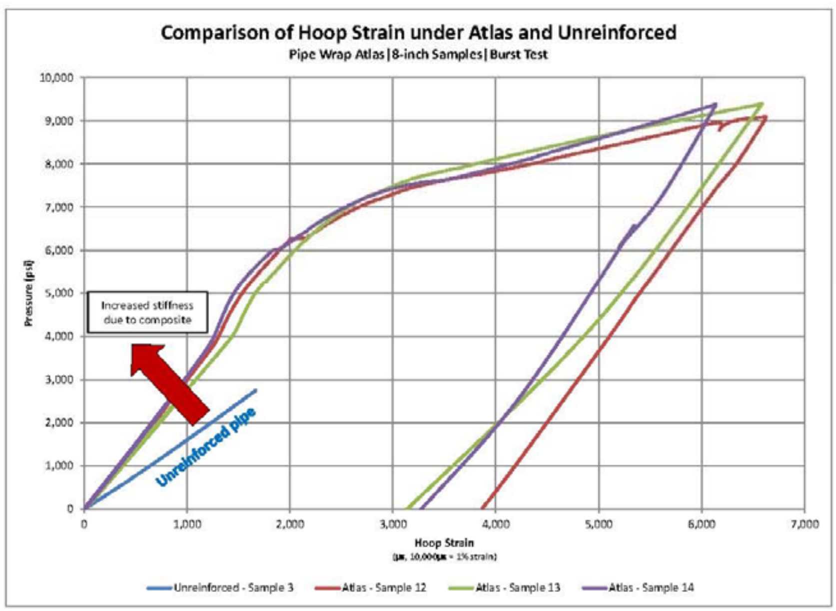

Figure 13: Pressure vs. Hoop Strain (8-inch Milliken-Pipe Wrap Atlas)

Figure 14: Photos Showing Burst Tests of Actual Reinforced Seam Planar Defects

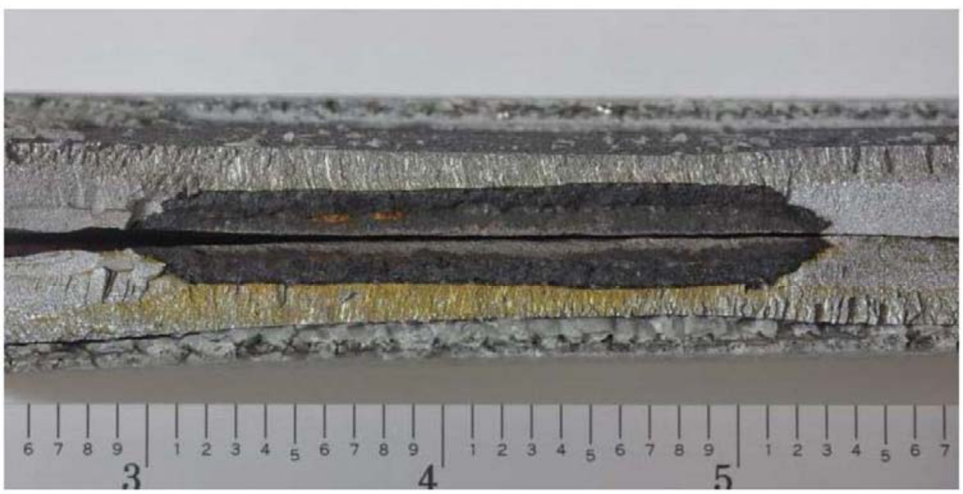

Figure 15: Post Flaw Inspection of EDM notch in Reinforced Sample (Failure Occurred outside Reinforcement)

Table 1: Target Number of Cycles for Reinforced and Unreinforced Samples

Repair Type	Nominal Pipe Diameter	Target Number of Cycles
Unreinforced	8 inches (203 mm)	150
	16 inches (406 mm)	350
Milliken-Pipe Wrap - Atlas	8 inches (203 mm)	1,500
	16 inches (406 mm)	3,500
Western Specialties - ComposiSleeve	8 inches (203 mm)	1,500
	16 inches (406 mm)	3,500

Table 2: Burst Test Samples – Pressures for various percentages of SMYS

Nominal Pipe Diameter	72% SMYS	90% SMYS	100% SMYS
8 inches (203 mm)	1,920 psi (13.24 MPa)	2,400 psi (16.55 MPa)	2,667 psi (18.39 MPa)
16 inches (406 mm)	1,460 psi (10.07 MPa)	1,825 psi (12.58 MPa)	2,028 psi (13.98 MPa)

Table 3: Summary of Pressure Cycling Results

Reinforcement Type	Nominal Pipe Diameter	Sample(s) #	Cyclic Pressure Ranges	Cycles Completed
Unreinforced	8-in (203 mm)	1	267–1,920 psi (1.84–13.24 MPa)	167 (failed during cycling) (NOTE)
Unreinforced	8-in (203 mm)	2, 3	267–1,920 psi (1.84–13.24 MPa)	150
Unreinforced	8-in (203 mm)	4	267–1,920 psi (1.84–13.24 MPa)	1 (Failed at 1,720 psi (11.86 MPa))
Unreinforced	8-in (203 mm)	10	267–1,920 psi (1.84–13.24 MPa)	1 (Failed at 1,554 psi (10.71 MPa))
Unreinforced	16-in (406 mm)	16	202–1,460 psi (1.39–10.07 MPa)	350
Milliken-Pipe Wrap - Atlas	8-in (203 mm)	12 - 14	267–1,920 psi (1.84–13.24 MPa)	1,500
Milliken-Pipe Wrap - Atlas	16-in (406 mm)	15	202–1,460 psi (1.39–10.07 MPa)	3,500
Western Specialties ComposiSleeve	8-in (203 mm)	5, 8, 9	267–1,920 psi (1.84–13.24 MPa)	1,500
Western Specialties ComposiSleeve	16-in (406 mm)	11	202–1,460 psi (1.39–10.07 MPa)	3,500

NOTE: This sample was in some regards "sacrificial" in that the original intent was to apply 1,000 pressure cycles to generate pre-crack in the EDM notch. However, after this sample failure and others failed after one cycle (i.e., Samples #4 and #10); all attempts to apply 1,000 cycles were abandoned.

Table 4: Average Burst Pressures of Unreinforced and Reinforced Samples

Reinforcement Type	Nominal Pipe Diameter	Number of Samples	Average Burst Pressure (if applicable)	% Increase from Unreinforced
Unreinforced	8 inches (203 mm)	6	2,428 psi (16.74 MPa)	N/A
	16 inches (406 mm)	1	2,304 psi (15.89 MPa)	N/A
Milliken-Pipe Wrap - Atlas	8 inches (203 mm)	3	9,283 psi (64 MPa)	382
	16 inches (406 mm)	1	6,440* psi (44.4 MPa)	280
Western Specialties ComposiSleeve	8 inches (203 mm)	3	4,019 psi (27.71 MPa)	166
	16 inches (406 mm)	1	3,478* psi (23.98 MPa)	151

Note: Only one (1) 16-inch pipe sample was tested for each configuration due to limited material.

Appendix G: Reinforcing Large Diameter Elbows Using Composite Materials Subjected to Extreme Bending and Internal Pressure Loading

Alexander, C., Vyvial, B., and Iyer, A. (Stress Engineering Services Inc.)
Kania, R. and Zhou, J. (TransCanada Pipeline LTD)

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IPC2016-64311

REINFORCING LARGE DIAMETER ELBOWS USING COMPOSITE MATERIALS SUBJECTED TO EXTREME BENDING AND INTERNAL PRESSURE LOADING

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas USA

Richard Kania
TransCanada Pipelines Limited
Calgary, Alberta Canada

Joe Zhou
TransCanada Pipelines Limited
Calgary, Alberta Canada

Brent Vyvial
Stress Engineering Services Inc.
Houston, Texas USA

Ashwin Iyer
Stress Engineering Services, Inc.
Houston, Texas USA

ABSTRACT

A study was conducted to evaluate the use of E-glass/epoxy composite materials for reinforcement of large-diameter elbows. Using a combination of sub-scale and full-scale testing, the study demonstrated that when properly designed and installed, composite materials can be used to reduce strain in reinforced elbows considering bending loads of up to 3.6 million ft-lbs (4.88 million N-m), cyclic pressures between 720 psi (4.96 MPa) and 1,440 psi (9.93 MPa), and burst testing. The stresses measured in the composite material were well below designated ASME PCC-2 design stresses for the composite materials. During testing, there was no evidence that previously applied bending loads reduced the overall burst pressure capacity of the composite-reinforced elbows. Finite element modeling was used to optimize the geometry of the composite reinforcement. The resulting design guidance from this study was used to provide direction for possible reinforcement of large-diameter elbows for in-service pipelines.

INTRODUCTION

This paper provides details on a study performed to evaluate the design and assessment of a composite reinforcement for 36-inch (900-mm) diameter 3D elbows. In conducting this study, full-scale destructive testing, sub-scale cold temperature testing, and numerical modeling using finite element analysis were used to validate the use of composite materials in this application. This paper provides results associated with the analysis and testing work that evaluated and validated the composite-reinforcement design.

Sections are provided with information on the aforementioned phases of work. The *Background* section provides some historical commentary on the use of composite materials in reinforcing high-pressure pipelines. Included is an *Analysis Methods and Results* section that provides an overview of the composite design optimization that was performed. The *Testing Methods and Results* section provides details on sub-scale and full-scale testing that was performed. These tests included composite coupon tests down to -40 °F (-40°C), tests to evaluate the effects of pressure during installation at anticipated ambient temperatures, testing to measure composite inter-layer strains, and full-scale testing that involved bending unreinforced and reinforced 36-inch (900-mm) diameter 3D 17° elbows prior to burst testing. The *Discussion* and *Closing Comments* sections provide information relating to the applicability of results to actual pipeline operation and insights associated with ensuring long-term performance of the composite reinforcement derived from previous experience.

BACKGROUND

Over the past decade the composite repair industry has benefitted with the development of industry standards such as ASME PCC-2 *Repair of Pressure Equipment and Piping* standard (Article 4.1, *Nonmetallic Composite Repair Systems: High-Risk Applications*). This standard provides guidance for the pipeline industry on how to properly design and qualify composite systems for repairing wall-loss corrosion damage in high-pressure pipelines. Not included in this standard (at the present time) are guidelines for explicitly designing composite systems to repair and reinforce features in high-pressure pipelines other than corrosion damage. Dating back to the mid-1990s, work has been conducted by numerous pipeline operators and repair companies to design composite-repair solutions to address issues such as the following[1]:

- Reinforcement of branch connections considering internal pressure, in-plane bending, and out-of-plane bending
- Repair of mechanical damage (dents with gouges) [8]
- Repair of plain dents, as well as dents interacting with ERW seam welds and girth welds [8]
- Reinforcement of wrinkle bends subjected to cyclic pressure and high-strain / low-cycle bending conditions [9]
- Reinforcement of vintage girth welds with 50% lack of penetration defects considering internal pressure, bending, and tension loads
- Reinforcement of crack-like features in pipes subjected to cyclic and burst pressures
- A study including full-scale testing to evaluate the use of composite materials for re-rating pipelines
- Design and assessment of a carbon-epoxy system used to reinforce offshore risers subjected to combined loads using finite element modeling and full-scale destructive testing [12-14]

The research programs in the above list served to provide valuable information and insights on the performance of composite repair technologies. The cumulative knowledge accumulated regarding the performance of composite repairs was important in completing the reported work and designing the system used in service.

[1] Only a partial list of the most pertinent studies has been provided.

In conducting these studies, a systematic method was developed for evaluating the performance of composite-repair systems considering diverse conditions. As can be noted from the preceding list, there is great variability in the types of studies that have been conducted, although each have contributed to the overall level of understanding.

The key to ensure that an appropriate design solution has been developed involves identifying the loading to be carried by the reinforcement and ensuring that stresses in the reinforced steel and composite material remain below designated design stresses. ASME PCC-2 has been a useful resource for providing industry (and this analysis) a methodology for establishing composite design stresses for long-term service.

Listed below are the specific steps used to evaluate the performance of composite systems for repairing and reinforcing pipelines.

1. Identify loading of the pipeline associated with the condition needing reinforcement. Examples include cyclic pressure for dents, bending and tension loads for vintage girth welds, and in-plane bending for welded branch connections.
2. Design the reinforcement necessary to provide the appropriate level of stiffness to the previously identified loading. Because of the diverse capabilities of composite systems in terms of their architecture (e.g., fiber orientation and thickness), matrix (resin) selection, and fiber type, this stage of the design process is extremely important. Provided below are several recommendations related to the design and optimization of the composite system.
    a. For reinforcement associated with axial tension and bending loads, fibers must be axially-oriented (relative to the axis of pipeline).
    b. The corollary to the preceding statement is also true: circumferentially-oriented fibers are necessary for loading associated with hoop stresses. This often includes the reinforcement of dents and corrosion.
    c. A legitimate starting point for determining composite thickness for any design is using the guidelines specified in ASME PCC-2 considering the highest permitted design pressure of the pipeline (i.e., 80% SMYS) assuming a corrosion depth of 80%. Although not all designs will require such a thick composite, it is best to utilize a thicker composite than actually required during the early stages of the design process.
    d. Finite element analysis modeling is an ideal means for quantifying the magnitude of reinforcement provided by competing composite technologies by considering variations in fiber type (i.e., elastic modulus), fiber orientation, length of reinforcement, and thickness of the reinforcement. Plots can be made to illustrate stress changes in the reinforced steel as functions of the selected variables. Limit-state analysis can also be performed by increasing the loading in question to a sufficient magnitude to cause failure in the reinforced steel; this requires elastic/plastic properties for the steel and a designated strain-to-failure condition for the composite materials.
    e. Once the design of the composite system has been selected and/or optimized, full-scale destructive testing should be conducted. The testing program should be designed to simulate actual pipeline field loading conditions, which often requires the use of large-capacity load frames. Additionally, strain gages should be used to measure strain in both the reinforced steel and composite materials. This includes installing strain gages within the reinforcing system itself to measure inter-layer strains, which can then be compared to allowable strains permitted in the composite by standards such as ASME PCC-2.
3. The last step in the design process involves documentation. This includes not only documenting all testing (sub-scale and full-scale) and analysis (finite element analysis modeling and hand calculations), but also integrating previous bodies of research that have contributed to the overall understanding of composite reinforcement for high-pressure pipelines.

ANALYSIS METHODS AND RESULTS

After the loading conditions representative of those actually present in the elbows were identified, the analysis efforts focused on the development of an optimized composite-reinforcement system. The intent was to design a repair configuration that minimized stresses in the reinforced steel. Four models were constructed using the same overall composite thickness, but varied by evaluating different fiber orientations (i.e. hoop and axial). Due to time limitations associated with the project schedule and the need for rapidly developing a composite design, a single thickness of 1.0 inch (25 mm) was selected for assessment.

The Armor Plate® Pipe Wrap (APPW) is an E-glass / epoxy composite repair system. It was selected because of the large number and wide range of testing programs to which it has been subjected, including the reinforcement of wrinkle bends and branch connections that are of especially applicable to the current body of work. Further, the APPW system satisfies the requirements of the ASME PCC-2 standard, ensuring that the composite system meets the requirements of CSA Z662-11 Article 10.11.4.3. Because the composite repair installations were completed in Canada, it was necessary for the repair to meet the requirements of the CSA Z662 standard.

Based on prior experience regarding composite repair performance and options regarding fiber orientation, four combinations of the reinforcement were considered, involving specific lay-up combinations of circumferentially (C) and longitudinally (L) oriented fibers as listed below. The numbers listed correspond to the number of layers for that particular orientation (e.g., "3C" is three circumferentially-oriented layers). As noted, a total of 16 layers were selected for each combination; corresponding to a thickness of 1.0 inch (25 mm).

- Option 1: 3C | 1L | 3C | 1L | 3C | 1L | 3C | 1L
- Option 2: 16C
- Option 3: 16L
- Option 4: 2C | 2L | 2C | 2L | 2C | 2L | 2C | 2L

Figure 1 shows the configuration for the finite element model, including the addition of the composite materials, which extended 36 inches (900-mm) (i.e., one pipe diameter) on each side of the elbow. Symmetry boundary conditions were applied to this model to simulate plane strain conditions; however, the temperature was held constant at 116 °F (46.7 °C) while internal pressure was increased to determine the condition at which yielding occurred.

The ABAQUS general-purpose finite element software was used to complete the analysis. Both the composite and pipe / elbow steel materials were modeled using four-noded shell elements (i.e. type S4R). No effort was made to model potential disbondment between the composite and steel; however, extensive work by Alexander both analytically and experimentally have demonstrated that disbondment does not occur when composite materials are used to reinforce large sections of pipe (length of at least 3 pipe diameters) subjected to bending loads of sufficient magnitude to cause yielding in the base pipe material. A mesh density of sufficient magnitude was used to ensure that the finite element model captured the maximum stresses (and strains) in the model.

From a constitutive modeling standpoint, the composite material was modeled elastically, while the pipe material was modeled using elastic perfectly-plastic materials properties assuming a Grade X70 material (i.e. yield strength of 70 ksi (483 MPa)). The elastic modulii for APPW in the circumferential and longitudinal directions were modeled as 3.93 Msi (27.09 GPa) and 0.65 Msi (4.48 GPa), respectively. These are lower-bound 95% confidence level values based on sub-scale coupon tests. It should be noted that APPW is comprised of a multi-axis fiber system with a majority of the fibers running parallel to the primary direction of the cloth. Therefore, when APPW is installed circumferentially, most of the fibers are oriented circumferentially, although some fibers are oriented in the axial direction.[2]

Figure 2 includes four contour plots for each of the composite design configurations, illustrating the effects of composite reinforcement on the internal pressures required to cause yielding. Listed below are the internal pressures required to cause yielding in the elbow.

- Option 1: 3C | 1L (occurs 4X) P_{yield} = 2,370 psi (16.34 MPa)
- Option 2: 16C P_{yield} = 2,397 psi (16.53 MPa)
- Option 3: 16L P_{yield} = 1,800 psi (12.41 MPa)
- Option 4: 2C | 2L (occurs 4X) P_{yield} = 2,098 psi (14.47 MPa)

In reviewing the preceding results, it is observed that the circumferential-only configuration (Option 2) provides the greatest level of reinforcement, while the longitudinal-only configuration (Option 3) provides the least amount of reinforcement. These results were as expected because elevated circumferential stresses in elbows due to bending are typically associated ovality; the presence of circumferentially-oriented fibers minimizes ovality to ensure a reduced stress state in the elbow. Most importantly, these results demonstrate that it is possible to design a composite reinforcement that ensures that yielding in the elbow will not occur when the composite material is present. From a pipeline design standpoint, if a composite material can prevent yielding from occurring in the reinforced pipe, the likelihood for ductile overloading is reduced from the operating scenario.

Figure 3 is a graph showing von Mises stress in the steel pipe at 1,440 psi (9.93 MPa) and 116 °F (46.7 °C) with APPW reinforcement. The von Mises stress in the pipe with the Option 2 reinforcement is 45.6 ksi (314.4 MPa), while even Option 3 provides some reinforcement as indicated by the steel having a stress of 59.3 ksi (408.86 MPa). These results confirmed that the circumferential-only configuration associated with Option 2 provides the greatest level of reinforcement; therefore, it was selected as the design configuration to be used.

[2] The following material properties were measured for APPW (S – tensile strength; E – elastic modulus; ε – strain at failure):

- Circumferential: S = 67,006 psi E = 3.93 x 10^6 psi ε = 1.70% (S = 461.95 MPa, E = 27.09 GPa)
- Longitudinal: S = 6,950 psi E = 0.86 x 10^6 psi ε = 0.81% (S = 47.91 MPa, E = 5.93 GPa)

TESTING METHDOS AND RESULTS

In conjunction with the analysis and numerical modeling work, sub-scale and full-scale testing was conducted as part of the validation effort. Testing included the following: coupon testing to measure material property changes at cold temperatures, a study to address the effects of internal pressure during installation, and full-scale testing on 36-inch (900-mm) pipe that included bending, pressure to failure, and quantifying strain distribution within the composite reinforcement.

A significant body of testing work was completed to evaluate and validate the performance of the composite reinforcing technology; however, due to space limitations in this paper, limited results are provided that include the following:

- Cold-temperature coupon testing
- Full-scale bending and burst testing
- Inter-layer strain tests to measure strains in the composite to quantify stresses relative to the allowable design stress for the composite material per ASME PCC-2.

The sections that follow provide specific details on these test efforts.

Cold-Temperature Composite Testing

The ability of a composite system to reinforce a pipeline is directly proportional to the stiffness and strength of the material. It is widely recognized that composite material properties (i.e., elastic modulus and tensile strength) are reduced with increasing temperature; however, minimal testing has been completed to address the effects of cold temperatures. The primary concern at elevated temperatures is loss in strength as the glass transition temperature is reached; however, at cold temperature, no material degradation factor is available other than it generally being understood that there is a potential for brittle behavior.

Because of questions related to the above subject matter, a series of coupon-level tests was conducted to quantify the material properties of APPW at cold temperatures. Coupon-level testing was performed at temperatures down to -40 °F (-40 °C) on two of Armor Plate's epoxy resin systems including the MP (Multi-purpose) and ZED cold temperature systems. The MP system can be used with a wide-range of installation temperatures; however, the ZED system was specifically formulated for cold-weather conditions where proper curing of the MP resin would be difficult. Included in Figure 4 and Figure 5 are tensile strength and elastic modulus data plotted for the MP and ZED systems as functions of temperature, respectively. As noted, the magnitude for both of these values generally decreases with decreasing temperature. Included in Figure 6 are photographs showing the test set-up and typical coupon failures.

What has not been included in the data plotted in Figure 4 and Figure 5 are the strain-to-failure measurements. Because of the concerns regarding the potential for brittle behavior, the issue of elongation was monitored closely. Listed below are the strain-to-failure (i.e., elongation) measurements recorded for the composite repair material at the four temperatures of interest.

- 70°F (21°C) 1.9%

- 32°F (0°C) 2.2%
- 0°F (-18°C) 2.2%
- -40°F (-40°C) 2.4%

It is clear that both the MP and ZED resin systems performed well at cold temperatures, with no loss in tensile strength and reduction in elongation. Additionally, there is no loss in elastic modulus at colder temperatures. There is also no indication of brittle behavior at any of the tested temperatures, observed in the average strain to failure for ZED system test coupons at -40 °F (-40°C) was 2.4%.

Full-scale Testing

Conducting full-scale tests was an essential part of the overall validation program. The intent was to subject the composite reinforcement to loads beyond those expected in actual service to demonstrate the integrity of the composite materials and quantify the magnitude of reinforcement provided to the elbow. Full-scale testing has been the primary means for validating composite repair technology and was a major focus of the current study.

In addition to testing the elbows, testing was performed to quantify strains in the composite material. This particular test, referred to as the *Inter-layer Strain* (ILS) test, has been used previously to quantify strains (i.e., stresses) in the composite system at design conditions; ensuring that the stresses in the system are less than the ASME PCC-2 designated design stresses.

A total of four full-scale destructive tests were conducted, including testing elbows in the unreinforced and reinforced conditions. Listed below are the full-scale samples that were tested:

- Unreinforced elbow burst test
- Reinforced elbow burst test
  - Prior to reinforcement, the unreinforced elbow was subjected to OPEN and CLOSE bending at 1.8 million ft-lbs
  - After installation of APPW, this same elbow (tested previously in the unreinforced condition) was subjected to OPEN bending at 1.8 million ft-lbs (2.44 million N-m) and CLOSE bending at 3.6 million ft-lbs (4.88 million N-m) prior to the burst test
- Unreinforced straight-pipe burst test (for comparison with the ILS test results)
- Reinforced ILS straight-pipe burst test

The bending loads in testing were based on results from a global finite element model that integrated internal pressure and thermal loading. The model also included pipe-soil interaction. The pipeline system in question experiences minimal pressure cycling; however, to demonstrate the ability of the composite material to function in reinforcing the elbows it was subjected to cyclic pressure loading prior to the application of bending loads. Extensive research by Alexander et al has demonstrated that composite materials are able to withstand significant pressure cycling and still provide reinforcement to damaged pipe sections (i.e. pressure cycling up to 750,000 cycles in reinforcing 75% corrosion in 12.75-inch x 0.375-inch (323.85-mm x 9.52-mm) pipe with a pressure range equal to 72% SMYS) [4, 8, and 9].

During testing the unreinforced elbow sample care was taken to not introduce plastic strains in the elbow that would have prevented a direct comparison between the unreinforced and reinforced test samples. Strain gage measurements and the linear load-deflection response confirmed that no plastic deformation was introduced when testing the unreinforced sample.

The sections that follow provide specific details on the tests on the above four pipe samples that included combinations of bending and pressure loads.

Elbow Bend Testing

Bend testing was conducted on one of the two 36-inch (900-mm) diameter 3D 17° elbows. Testing was conducted in both the unreinforced and reinforced conditions. The same elbow was tested in these two configurations to ensure a direct comparison of results for the unreinforced and reinforced conditions. A second elbow was tested in the unreinforced condition, but was only subjected to a burst pressure test (i.e., no bend testing); serving as the reference case for the subsequent reinforced elbow burst test.

The following steps were performed in conducting tests on the **UNREINFORCED** sample.

- Pressurized sample to the 100% SMYS pressure of 1,790 psi (12.34 MPa). Held for 10 minutes.
- De-pressurized the sample to the design pressure of 1,440 psi (9.93 MPa). This pressure was held constant throughout the bend test.
- Applied a bending moment of 1.8 million ft-lbs (2.44 million N-m) (design conditions provided by AP Dynamics based on a global finite element model).
- Removed bending moment.
- Applied bending moment repeatedly to achieve a total of 3 bending cycles.
- Loads were applied to the elbow test sample to generate bending in the OPEN and CLOSE modes. The test sample was designed to permit rotation of the sample between these two phases of loading.
- Removed the applied bending load and reduced the internal pressure to 0 psi.

After testing was conducted on the sample in the unreinforced condition, the sample was reinforced with APPW. A total of 16 layers of the composite material were installed, resulting in a total composite thickness of 1.0 inch. The steps associated with this phase of testing are as follows:

- Composite materials installed with an internal pressure of 1,038 psi (7.16 MPa) held constant.
- Pressurized sample to the 100% SMYS pressure of 1,790 psi (12.34 MPa). Held for 10 minutes.
- De-pressurized the sample to the design pressure of 1,440 psi. This pressure was held constant throughout the bend test.
- Applied a bending moment of 1.8 million ft-lbs (2.44 million N-m) in the OPEN mode.
- Applied a bending moment of 3.6 million ft-lbs (4.88 million N-m) in the CLOSE mode.
- Applied bending moments repeatedly to achieve a total of 3 bending cycles in both the OPEN and CLOSE modes.
- Removed the applied bending load and reduced the internal pressure to 0 psi.
- Removed test sample from bending frame and moved for burst testing.

Figure 7 through Figure 9 provide photographs of the bending sample at various stages of testing. Of particular importance is the configuration of the test sample that permitted it to be loaded so that bending loads could be applied to open and close the elbow. As noted above, bending loads were applied to the test sample in the unreinforced condition before the composite material was applied.

Strain gages were installed on the test sample to measure hoop and axial strains. The strain of interest was measured by the gage located at the intrados of the bend. Table 1 provides hoop and axial strain measurements at the intrados of the elbow during bend testing, including the unreinforced and reinforced conditions in the OPEN and CLOSE modes. Using the bi-axial stress/strain relation, hoop and axial stresses were calculated using the strain measurements and are included in the table.

Several observations are made based on the data provided in Table 1.

- With bending moments up to 1,000 kip-ft (1.356 million N-m) in the CLOSE mode, the composite reinforcement reduces the magnitude of both hoop and axial stresses; in the OPEN mode, stress is reduced for the full range of applied bending moments.
- The presence of the composite reinforcement significantly reduces the stress changes that occur in the elbow with increasing bending loads.
- The OPEN mode generates larger hoop stresses at the intrados of the elbow.
- As expected, the CLOSE mode generates elevated compressive axial stresses at the intrados of the bend.

Elbow Burst Testing

After all phases of bending testing were completed, the reinforced elbow was burst tested. A second sample was also fabricated using another elbow to permit burst testing of an unreinforced elbow (no bending loads were applied to this second sample prior to burst testing). The following sections provide results for burst testing conducted on the unreinforced and reinforced elbows.

Burst Test of Unreinforced Elbow

During pressure testing, the reinforced elbow sample was pressurized to the following pressures and held for 10 minutes at each level.

- 1,038 psi (7.16 MPa) (58% SMYS, as a point of reference, this was the composite installation pressure)
- 1,440 psi (9.93 MPa) (80% SMYS, design pressure)
- 1,611 psi (11.11 MPa) ((90% SMYS)
- 1,790 psi (12.34 MPa) (100% SMYS)

The unreinforced sample failed at a pressure of 2,952 psi (20.35 MPa). The failure occurred at the intrados of the bend as a longitudinally-oriented fracture in a ductile manner as shown in Figure 10. Strain gages were monitored during testing; results are presented and discussed in a subsequent section of this report.

Burst Test of Reinforced Elbow

A burst test was conducted on the reinforced elbow sample after it had been subjected to the bending tests as described previously. In addition to the pressure holds applied to the unreinforced sample, several additional load steps were applied to the reinforced sample that included the following.

- A 4 hour hydrotest at 1,790 psi (12.34 MPa).
- After hydrotesting, the sample was cycled between 720 psi (4.96 MPa) and 1,440 psi (9.93 MPa) to achieve a total of 10 pressure cycles.

As shown in Figure 11, the burst test failure of the reinforced elbow sample occurred outside the elbow and reinforcement in the base pipe, which had a wall thickness of 0.75 inch (19-mm). The failure pressure was 4,000 psi (27.58 MPa).

Comparison of Unreinforced / Reinforced Elbow Test Results

In addition to obtaining the burst pressures, the team measured hoop and axial strains on the intrados of the bend at various pressure levels. Table 2 provides the hoop and axial strain measurements and corresponding stresses as functions of internal pressure. Stresses at pressures exceeding 1,790 psi (100% SMYS) are not included because of the yielding of the pipe; once steel is loaded beyond the proportional limit[3], the linear relationship between stress and strain no longer exists. Of particular interest are hoop strains measured at the following pressure levels:

- At 1,440 psi (9.93 MPa): (80% SMYS, or MAOP):
  - Unreinforced: 2,512 με
  - Reinforced: 1,811 με
- At 1,790 psi (12.34 MPa): (100% SMYS):
  - Unreinforced: 3,104 με
  - Reinforced: 2,203 με
- At 2,400 psi (16.55 MPa): (134% SMYS)
  - Unreinforced: 7,576 με
  - Reinforced: 3,078 με

In reviewing the above data, as well as the results provided in Table 2, it is clear that the composite material reduces strain in the reinforced section of the elbow. This strain reduction is the primary reason that the composite materials were installed. At the design pressure of 1,440 psi, the reduction in hoop strain due to the composite reinforcement is greater than 25%.

Inter-layer Strain Testing

As mentioned previously, the ILS test is an effective means for validating the design stress of a composite repair system relative to the designated design stress from ASME PCC-2. For purposes of this test, a 36-inch x 0.500-inch (914.4-mm x 12.7-mm), Grade X70 pipe material was selected. The actual measured yield and tensile strengths were 88.1 ksi (607.43 MPa) and 98.1 ksi (676.38 MPa), respectively. Two tests were conducted as part of this effort that included pressure testing both reinforced and unreinforced samples. The reinforced sample was fitted with 16 layers of APPW, which corresponds to a composite thickness of 1.0 inch. This is the same thickness used to reinforce the elbow samples.

As with all phases of testing in this study, strain gages were installed on the pipe beneath the composite reinforcement. The ILS samples did not have any defects, anomalies, or components having stress concentration factors. The purpose of the test was to quantify the level of reinforcement provided by the composite in terms of strain reduction and increase in burst strength, as well as quantifying the stress in the composite material as a function of internal pressure. The unreinforced sample failed at a pressure of 2,966 psi (20.45 MPa), while the reinforce sample failed at a pressure of 3,623 psi

[3] Up to the "proportional limit" stress (σ) is proportional to strain (ε) based on Hooke's Law. The stress/strain graph is a straight line and the gradient (i.e., slope) is equal to the elastic modulus of the material ($E = \sigma/\varepsilon$).

(24.98 MPa) in the end cap. Had the end cap not failed, the burst pressure of the reinforced sample would have been greater. Table 3 provides a summary of the stress and strain results for the two ILS tests. As observed, at pressures exceeding 1,400 psi (9.93 MPa), the composite reinforcement reduces stresses in the reinforced steel. In Table 3, stresses exceeding 1,944 psi (13.4 MPa) (100% SMYS for this pipe material) are not included because of the yielding of the pipe. Of particular interest are hoop strains measured at the following pressure levels:

- At 1,750 psi (12.07 MPa): (90% SMYS):
    - Unreinforced: 1,796 με
    - Reinforced: 1,245 με
- At 1,944 psi (13.4 MPa): (100% SMYS):
    - Unreinforced: 1,991 με
    - Reinforced: 1,380 με
- At 2,400 psi (16.55 MPa): (134% SMYS):
    - Unreinforced: 2,457 με
    - Reinforced: 1,872 με

As with the elbow test samples, the composite materials effectively reduced strain in the reinforced steel. Even at the 90% SMYS pressure condition, the effect of the reinforcement is significant. Another objective in the ILS testing was to quantify the composite stress at design conditions (80% SMYS) to ensure that stresses in APPW did not exceed the design stress of 11,918 psi.[4] Plotted in Figure 12 is the composite hoop stress as a function of layer in the ILS reinforced sample. The hoop stress plotted in this figure was calculated using the strain gage measurements in conjunction with the elastic modulus of 4.4 Msi (30.34 GPa) for the APPW material. A maximum composite stress of 5,486 psi (37.82 MPa) was calculated, which is less than the composite design strength of 11,918 psi (82.17 MPa). Considering the data plotted in Figure 12, the average composite stress is more on the order of 3,000 psi (20.68 MPa).

The results of the ILS test demonstrate that stresses in the composite material are well below the design stress for APPW. Also, consistent with results for the elbow tests, the composite material is effective at reducing stress in the reinforced steel, and its presence ensures a significant increase in burst strength.

DISCUSSION

One of the challenges associated with evaluating the performance of composite-reinforced pipelines is the inter-dependent relationship between the steel pipe material and the composite system. The use of strain gages is extremely valuable for quantifying load transfer and measuring strains in the composite and reinforced steel, especially at design conditions. The results of this study are a model for the pipeline industry in how numerical modeling and full-scale testing can be used to evaluate the effectiveness of a composite reinforcement.

From a design standpoint, it is clear that at design conditions stresses in the composite material are less than the ASME PCC-2 design stress of 11,918 psi (82.17 MPa) for the Armor Plate® Pipe Wrap system. Results from the ILS study indicate that the average stress in the composite was on the order of 3,000 psi (20.68 MPa). This is especially important from a long-term standpoint as the key from a design standpoint is to ensure that large safety factors are present in the composite material. Considering that the average tensile strength for the Armor Plate® Pipe Wrap ZED system at room temperature is 68.6 ksi (472.98 MPa), a safety factor on the order of 22 exists. Although one could argue that the current design is overly conservative, in view of the critical role these elbow reinforcements are serving, one could hardly argue against the robust design.

A question often posed regarding the use of composite materials used to reinforce pipe sections subjected to bending loads concerns the interfacial bond between the steel and inner layers of the composite material. Significant research that includes more than 25 full-scale bend tests has demonstrated that as long as the thickness of the composite (approximately 1.5 times the thickness of the steel) and length of the repair (at least three pipe diameters) are adequate there is no reason to be concerned about the development of disbondment. Significant work was conducted by Alexander both experimentally and analytically in addressing this issue that included including evaluating the effects of large areas of disbondment [14].

Another critical aspect of the current study is the complex nature of the combined load cases. The full-scale testing efforts applied bending moments on the order of 2 times those expected in service, yet when tested there appeared to be no degradation in performance. The extreme bending load of 3.6 million ft-lbs (4.88 million N-m) is two times that maximum bending design moment of 1.8 million ft-lbs (2.44 million N-m) associated with the pipeline design. This extreme value was selected to demonstrate the range of performance capabilities associated with the composite reinforcing technology. The mindset was that if the composite reinforcing system could withstand a bending that was two times design conditions and still reinforce the pipe during burst testing, engineers could proceed with confidence in its use.

Additionally, the strains measured in the reinforced steel were clearly reduced considering the presence of bending loads (opening and closing the elbow) and internal pressure. The composite reinforcement is effective at lowering the von Mises stress state to ensure that yielding does not occur at design conditions. The reduction of the hoop stress due to the presence of the composite materials reduces the stress state in the elbow.

Stresses are of primary concern for composite repairs because the long-term performance in PCC-2 is established based on 1,000-hr tests (and the design Equation 12). Confirming the long-term performance of the composite was critical in this study and correlating the measured results back to the ASME PCC-2 allowable stress was essential. As noted throughout this paper, this work is basically a limit state design that is at its core strain-based. Therefore, when evaluating the performance of the steel elbow it is appropriate to use strains.

A final comment is with regard to an aspect essential to the success of this study, that is, the use of elastic-plastic data to quantify the true benefits of the composite reinforcement via limit-state design. Although typically achieved using numerical modeling, limit-state design can also be accomplished using full-scale testing. The approach involves the loading of a structure into the plastic regime (i.e., well beyond the proportional limit) to determine the load at which unbounded displacements occur. Unbounded displacements

[4] The design strength of 11,918 psi (82.17 MPa) for Armor Plate Pipe® Wrap is based on 1,000-hour long-term testing completed as part of the ASME PCC-2 certification. This includes a safety factor of 2.0 on the long-term strength for the composite material.

occur in steel when gross plasticity develops and significant levels of displacement occur with minimal increases in loading.

CONCLUSIONS

This paper has provided a summary of results associated with a comprehensive study completed to quantify the benefits of installing composite materials on 36-inch (900-mm) elbows. There are three important conclusions associated with this study. First, a composite repair system was designed that was effective in reinforcing the elbow to ensure that the calculated design pressure exceeded 80% SMYS based on finite element modeling. Secondly, the experimental work confirmed that the 1inch thick, circumferentially-oriented composite reinforcement generated a design pressure of 1,800 psi (12.4 MPa), which is 25% greater than the MAOP of 1,440 psi (9.93 MPa). Finally, from a long-term design standpoint the average stress in the composite is approximately 25% of the ASME PCC-2 allowable design stress for the APPW composite repair system.

This body of work represents a comprehensive approach for not only designing a composite repair system to reinforce high pressure pipelines subjected to combined loading conditions, but an approach for integrating analysis and testing to validate the design. The approach is a model for other complex applications of composite repair technologies.

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Table 1: Strain measurements at intrados of elbow during bend testing

	Open Position							
	Unreinforced				Reinforced			
Bending Moment kip-ft (million N-m)	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
500 (0.67)	2,387	656	85.1 ksi (586.75 MPa)	45.2 ksi (311.64 MPa)	1,818	599	65.9 ksi (454.37 MPa)	37.7 ksi (259.93 MPa)
1000 (1.356)	2,472	1,169	93.1 ksi (641.91 MPa)	63.0 ksi (434.37 MPa)	1,787	998	68.8 ksi (474.36 MPa)	50.6 ksi (348.88 MPa)
1800 (2.44)	2,590	1,996	105.1 ksi (724.64 MPa)	91.4 ksi (630.18 MPa)	1,738	1,662	73.7 ksi (508.15 MPa)	72.0 ksi (496.43 MPa)
3600 (4.88)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

	Closed Position							
	Unreinforced				Reinforced			
Bending Moment kip-ft (million N-m)	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
500 (0.67)	2,243	-171	72.2 ksi (497.8 MPa)	16.5 ksi (113.76 MPa)	1,784	-45	58.7 ksi (404.72 MPa)	16.2 ksi (111.70 MPa)
1000 (1.356)	2,152	-657	64.5 ksi (444.71 MPa)	-0.4 ksi (-2.76 MPa)	1,820	-434	58.7 ksi (404.72 MPa)	3.7 ksi (25.51 MPa)
1800 (2.44)	2,010	-1,389	52.5 ksi (361.98 MPa)	-25.9 ksi (-178.58 MPa)	1,888	-1,037	59.2 ksi (408.17 MPa)	-15.5 ksi (-106.87 MPa)
3600 (4.88)	N/A	N/A	N/A	N/A	1,712	-2,484	49.1 ksi (338.53 MPa)	-65.0 ksi (-448.16 MPa)

Table 2: Stress and strain results for reinforced and unreinforced elbow burst tests

Unreinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,038 psi (7.16 MPa)	1,820	136	61.3 ksi (422.65 MPa)	22.5 ksi (155.13 MPa)
1,440 psi (9.93 MPa)	2,512	204	84.8 ksi (584.68 MPa)	31.6 ksi (217.88 MPa)
1,611 psi (11.11 MPa)	2,799	235	94.6 ksi (652.25 MPa)	35.4 ksi (244.08 MPa)
1,790 psi (12.34 MPa)	3,104	265	105.0 ksi (723.95 MPa)	39.4 ksi (271.65 MPa)
2,400 psi (16.55 MPa)	7,576	167		
2,800 psi (19.31 MPa)	4,059	69		
2,952 psi (20.35 MPa) (BURST)	4,163	183		
Reinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,038 psi(7.16 MPa)	1,364	173	46.7 ksi (321.99 MPa)	19.2 ksi (132.38 MPa)
1,440 psi (9.93 MPa)	1,811	249	62.2 ksi (428.86 MPa)	26.1 ksi (179.95 MPa)
1,611 psi (11.11 MPa)	1,998	283	68.7 ksi (473.67 MPa)	29.1 ksi (200.64 MPa)
1,790 psi (12.34 MPa)	2,203	320	75.8 ksi (522.63 MPa)	32.3 ksi (222.7 MPa)
2,400 psi (16.55 MPa)	3,078	420		
2,800 psi (19.31 MPa)	5,732	370		
3,200 psi (22.06 MPa)	8,960	430		
3,600 psi (24.82 MPa)	12,495	737		
4,000 psi (27.58 MPa) (BURST)	16,988	1,221		

Table 3: Stress and strain results for reinforced and unreinforced ILS burst tests

Unreinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,400 psi (9.65 MPa)	1,110	421	40.8 ksi (281.31 MPa)	24.9 ksi (171.68 MPa)
1,750 psi (12.07 MPa)	1,245	471	45.7 ksi (315.09 MPa)	27.8 ksi (191.68 MPa)
1,944 psi (13.4 MPa)	1,380	521	50.7 ksi (349.57 MPa)	30.8 ksi (212.36 MPa)
2,400 psi (16.55 MPa)	1,872	721		
2,800 psi (19.31 MPa)	2,343	926		
3,200 psi (22.06 MPa)	3,748	1,250		
3,600 psi (24.82 MPa)	6,129	1,699		
3,623 psi (24.98 MPa) (BURST)	6,275	1,728		
Reinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,400 psi (9.65 MPa)	1,077	260	38.1 ksi (262.69 MPa)	19.2 ksi (132.38 MPa)
1,750 psi (12.07 MPa)	1,796	458	63.7 ksi (439.20 MPa)	32.8 ksi (226.15 MPa)
1,944 psi (13.4 MPa)	1,991	512	70.7 ksi (487.46 MPa)	36.6 ksi (252.35 MPa)
2,400 psi (16.55 MPa)	2,457	640		
2,800 psi (19.31 MPa)	15,922	773		

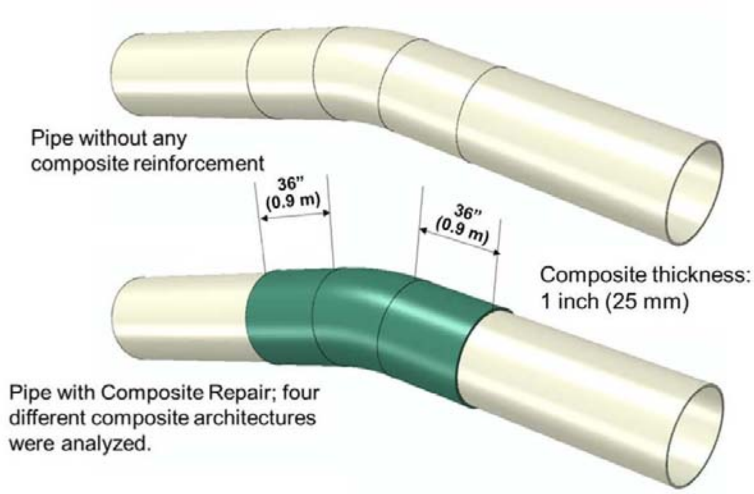

Figure 1: Finite element model showing composite reinforcing materials
(Note that 36 inches = 0.92 meters | 1.0 inch = 25.4 mm)

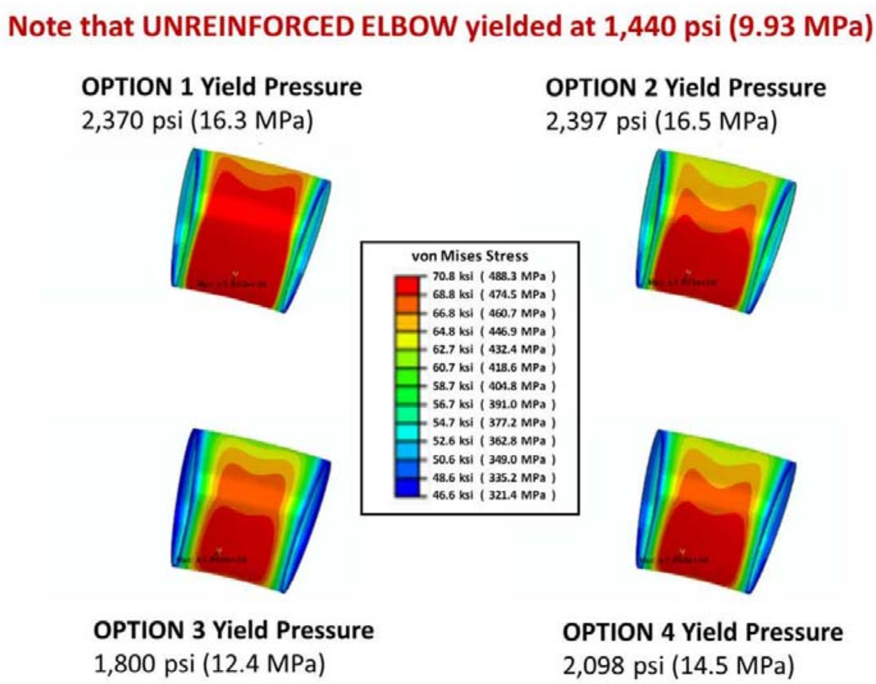

Figure 2: Effects of composite reinforcement on pressure required to cause yielding

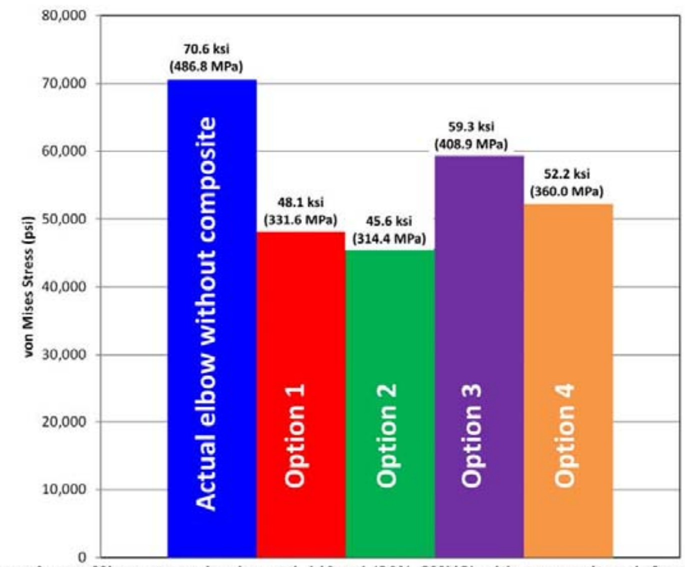

Figure 3: von Mises stress in pipe at 1,440 psi (80% SMYS) with composite reinforcement
Option 1: 3C / 1L (occurs 4X) | **Option 2:** 16C | **Option 3:** 16L | **Option 4:** 2C | 2L (occurs 4X)

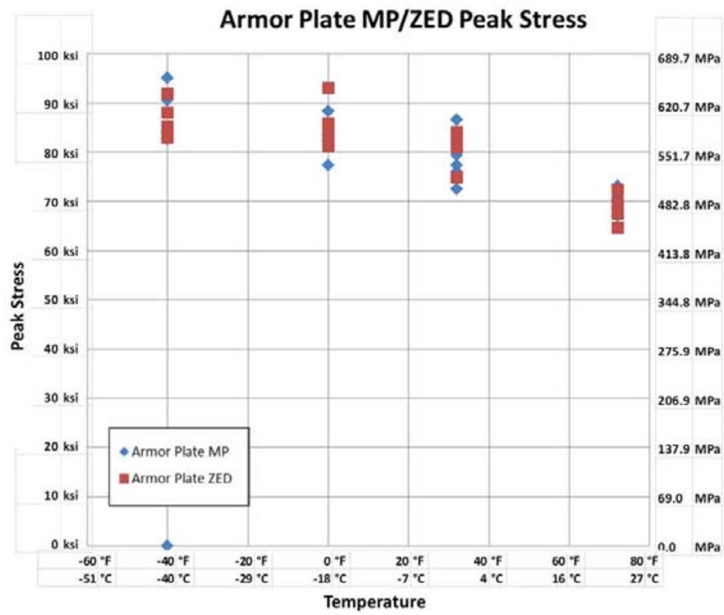

Figure 4: APPW tensile strength as a function of temperature (two resin systems)

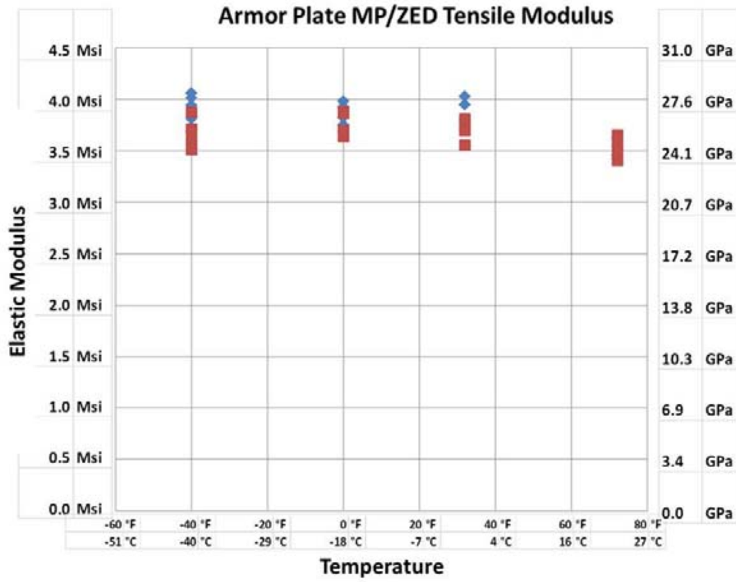

Figure 5: APPW elastic modulus as a function of temperature (two resin systems)

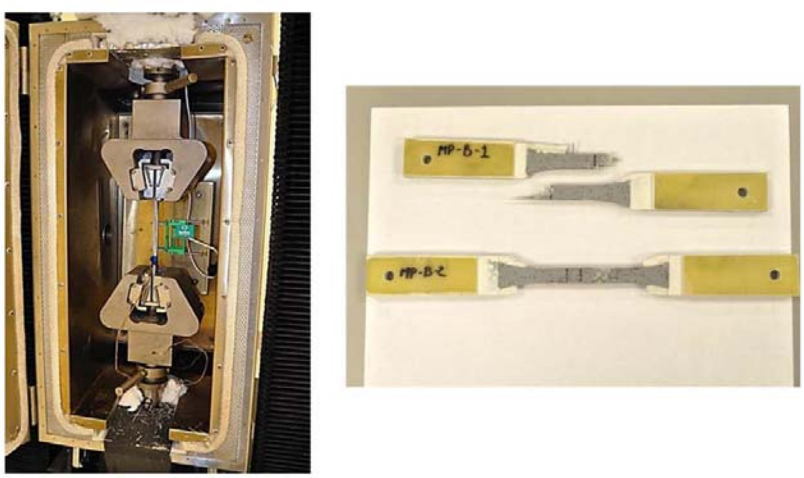

Figure 6: Photographs showing the test set-up and typical coupon failures

Figure 7: Unreinforced sample on bending beam in CLOSE mode

Figure 8: Close-up view of unreinforced sample on bending beam in OPEN mode

Figure 9: Aerial view of reinforced sample in bending load frame

Figure 10: Burst test failure of unreinforced elbow sample

Figure 11: Burst test failure of reinforced elbow sample

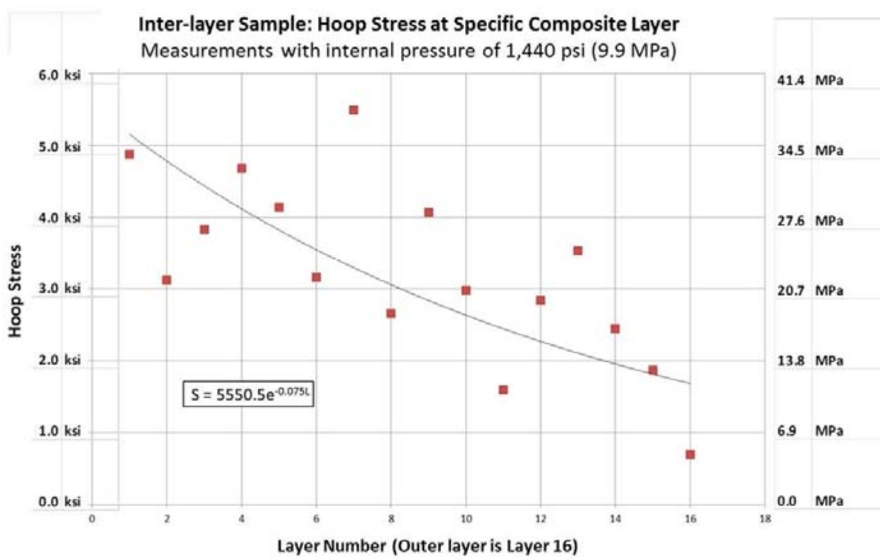

Figure 12: Composite hoop stress as a function of layer in ILS reinforced sample
(Equation provided above relates Hoop Stress (S) to Layer Number (L), units of ksi)