Paper 36

INSIGHTS GAINED THROUGH THE DEVELOPMENT OF A ROADMAP FOR COMPOSITE REPAIR SYSTEMS

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ABSTRACT

Over the past 20 years, composite materials have been used around the world to repair pipeline anomalies including corrosion, dents, bends, and branch connections. Since 2007 the Pipeline Research Council International, Inc. (PRCI) has taken an active role in funding research programs focused on evaluating composite repair technology. To date, PRCI has sponsored seven different programs focused on evaluating composite materials used to provide structural reinforcement.

Because of the significant investment by PRCI and other organizations, a Composite Roadmap was initiated to connect past, present, and future research efforts. In this paper, the authors present a roadmap for composite repair systems identifying how previous and ongoing research efforts contribute to industry's understanding in using non-metallic repairs. Of particular interest is a graphical *Composite Repair Roadmap Grid* that highlights lessons learned from prior efforts, while also identifying knowledge gaps in the current use of composite materials.

Included in this discussion are three PRCI projects that include the MATR-3-4 study to evaluate the long-term performance of composite materials in reinforcing externally-corroded pipes, the MATR-3-5 study focused on the repair of dents and mechanical damage, and the MATR-3-7 program that evaluated the reinforcement of vintage girth welds.

This paper will contribute to the international pipeline community's overall understanding of composite material performance and provide guidance for areas in need of further research.

1.0 INTRODUCTION

Since 2007 the Pipeline Research Council International, Inc. (PRCI) has supported projects for the gas and liquid transmission pipeline industries in evaluating composite repair technologies. During this time, PRCI has sponsored eight programs (seven focused on structural reinforcement and one focused on non-destructive examination) that integrated composite repair materials. Along with PRCI, individual pipeline operators and composite manufacturers have funded programs resulting in more than $7 million in research since 2007. Recognizing the important strides that have been made during this time period and observing the need for an intentional path forward, PRCI formed the *Composite Systems Roadmapping Working Group* Technical Committee of the Design, Materials, and Construction (DMC) Committee to develop a Composite Roadmap.

The three-fold goals of the Composite Roadmap are focused on expanding applications for which composite repairs, also known as non-metallic repairs (NMRs) can be used. The first goal of the Composite Roadmap is to identify the capabilities and limitations by executing technical projects and testing. The second goal is to improve confidence of operators and regulators in the use of NMRs for repairing pipelines and process applications over conventional repair techniques. The third goal of the Composite Roadmap is to improve the value of NMRs in comparison to other repair techniques by expanding the technical foundation for the use of NMRs.

In accomplishing the goals associated with the Composite Roadmap, there are numerous outcomes and benefits for industry. The roadmap will be used to define the boundary between known high-confidence applications and applications where additional research is required. A critical part of the broad-based acceptance of NMRs involves QA/QC programs associated with materials and installation techniques, as well as defining NDE techniques and defining acceptance criteria for flaws identified during the inspection process. In looking forward, the Composite Roadmap will be used to provide guidance for evaluating the integrity of existing composite repair systems. A final noteworthy contribution of the roadmap will be to influence industry standards including ASME PCC-2, ISO 24817, ASME B31.4, and ASME B31.8.

A core feature of the Composite Roadmap is identifying gaps that exist in the body of research that has been conducted by the pipeline industry and composite manufacturers over the past 20 years. The *Composite Repair Roadmap Grid*, shown in **Figure 1**, graphically presents an assessment of the research to date on NMRs and identifies areas requiring further study. The color-coding provides an effective means for identifying well-established uses of NMRs, as well as areas lacking adequate knowledge and experience. As an example, consider the repair of two anomaly types: external corrosion and seam welds. As observed in **Figure 1**, the “across the board” green cells associated with external corrosion indicate that this area is well understood and widely applied. However, the continuous red cells associated with the reinforcement of seam welds indicate there is an inadequate level of research and experience to support the use of NMRs in this application.

The sections of this paper that follow provide an overview of the existing PRCI composite research programs, including technical material associated with three of the research programs. A *Discussion* section provides insights on where PRCI is focusing in terms of upcoming research programs based on identified knowledge gaps. Finally, a *Closing Comments* section provides concluding remarks in relation to the composite roadmap effort.

Pipeline Anomaly, Technical Issue, or Feature	PRCI Research	Actual Field Installations	Guidance from Standards (ASME & ISO)	Independent Research	Consider PRCI ProjecT?	Comments
External corrosion					No	However, the effects of cyclic pressure need to be addressed in guidance document
Plain dents subjected to cyclic pressure					No	
Dents in welds (seam and girth) subjected to cyclic pressure					No	
Use of NMR's for Dents with metal loss					Maybe	Awaiting input from mechanical damage projects (MD-4). Gouge must be ground out. Includes corrosion and gouges.
Seam weld defects					No	Reconsider at later date for future project
Vintage girth welds (pressure, tension, bending)					No	Including welds with cracks (MATR-3-7)
Wrinkle bends					No	
Reinforced branch connections					No	Company-specific interest, Reconsider at later date
Use of NMR's for Elbows and bends					Yes	Incl. Cold Field Bends as well as induction bends
Forged Tees					No	Reconsider at later date for future project
Subsea + shallow water installations					No	Current PRCI project ongoing
Internal corrosion (non-leaking)					No	Not recommended
Use of NMR's to repair External Stress corrosion cracking (SCC)					Maybe	Reconsider at later date for future project
Corrosion > 80%					No	Not recommended
Uprating (re-rating) pressure					No	Out of Frame
Establshing/Maintaining MAOP					No	Current PRCI project ongoing
Repair of leaks					No	Not recommended
Effects of cyclic pressure & hydrotest on corrosion (fatigue design)					No	Will be addressed in guidance document
NDE Techniques and Acceptance Criteria					Yes	Requires co-ordination with O&I committee. Specific interests in (1) verification of presence of filler and (2) presence and strength of composite/steel bond and (3) moisture detection. **Include as initial phase:** Survey, Lit Review, Forensics of Field and Lab Failures. Notes:
Load Transfer and Delamination/Disbondment in NMR's: (Temperature, Pressure, and Filler Material Effects)					Yes	**Delamination and Disbondment**: Causes include assessment of (1) pressure during installation, (2) thermal expansion/contraction, (3) pressure fluctuations. Significance refers to loss of performance due to these defects. Also concern over load transfer for **NMR's applied at high pressure**. Consider old and new tests both. Validations would be required across a range of pipe sizes and conditions. Include general **Filler Material requirements** (not just temp/pressure specific) as a milestone. refer to filler materials from failed tests. *Outstanding question re: strength vs. diameter.
Performance at elevated temperatures (140F<T<250F)					Maybe	To be addressed in guidance document (Exact temperature range TBD)
Use of Composites as Crack Arrestor					Maybe	Definitely in guidance document as Gap Analysis Only. Consider quick-kill paper study/review. Particular emphasis on X80+
Validation of PCC-2 Design for Composite Repairs on High Grade Steels (X65+)					No	quick-kill paper study/review. Particular emphasis on X80+. If an issue with PCC-2 is found, suggest changes.
Identify/Develop techniques to allow detection of composite repairs by ILI tools					No	Roadmap to provide guidance on MFL markers in composite repair. Corrosion and dents. Future development oriented toward Pig Marker for UT and geometry tools. Require ILI-MFL vendors to report metal in close proximity.
Develop guidance for conducting a failure analysis of composite wrap repairs					No	Compiling existing failure data and establishing terminology to capture composites failure modes may be Phase 1.

Color Code	
	All necessary work has been completed in this area
	Some work completed but more work required
	Minimal to no experience
	N/A

Figure 1: Composite Repair Roadmap Grid
(Refer to above *Color Code* chart for details on research assessment levels)

2.0 PRCI COMPOSITE RESEARCH PROGRAMS

Listed below are the composite repair research programs sponsored by the PRCI DMC Committee and foundational elements in the Composite Roadmap:

- MATR-3-3 Assessing Composite Systems for Pipeline Repair
- MATR-3-4 Long Term Testing of Composite Repair Systems for External Corrosion Repair
- MATR-3-5 Composite Repair of Mechanical Damage
- MATR-3-6 Composite Repair of Subsea Pipelines
- MATR-3-7 Composite Reinforcement of Vintage Girth Welds
- MATR-3-9 Composite Reinforcement for Re-rating Pipelines
- MATV-1-2 Assessment of Wrinklebends (composite repair included as a subset of testing program)

In addition to the PRCI research programs, the Gas Technology Institute has conducted research programs focused on assessing composite reinforcement, as well as research sponsored by U.S. regulatory bodies. Additionally, numerous independent research programs have been sponsored by composite manufacturers in the development and qualification of their respective repair systems.

The sections that follow provide specific information on the MATR-3-4 long-term study, MATR-3-5 dent study, and the MATR-3-7 girth weld reinforcement study. The intent in presenting information and results for these specific programs is to convey the breadth of knowledge associated with these studies and their contribution to increasing the pipeline industry's knowledge regarding composite repair technology.

2.1 MATR-3-4 Long-term Study

At the present time there is relatively wide acceptance in using composite materials to repair externally corroded gas and liquid transmission pipelines, although an ongoing concern has been the long-term performance of composite repair systems used to repair corrosion and other anomalies. Although there have been numerous independent research programs performed by pipeline companies, research organizations, and manufacturers, none have sufficiently evaluated the degradation of composite repair systems as a whole. To address long-term performance, PRCI initiated the MATR-3-4 program, *Long-Term Composite Repair Study*, where samples with simulated corrosion were repaired with composite materials and buried for up to 10 years. Co-sponsors of this program included 13 composite manufacturers who provided in-kind material donations, installation personnel, and significant financial contributions.

The minimum period of testing for the MATR-3-4 study was 3 years, although 5 companies elected to provide additional resources and capital to test their systems for up to 10 years. The program involved repairing 12-inch NPS pipe samples that had 40, 60, and 75% deep corrosion regions machined into the test pipes. A schematic diagram showing the machining details for the simulated corrosion samples is shown in **Figure 2**, while **Figure 3** is a photograph showing the machined region with strain gages installed. The strain gages were initially used to quantify the level of reinforcement provided by each repair system (after burial some of the gages were not able to provide meaningful strain measurements).

An initial round of samples was burst tested and these samples are designated as the Year 0 burst tests. The burst test results are the subject of this particular report. Additionally, 144 samples were buried as shown in **Figure 4,** were pressure cycled, and removed for burst testing at 1, 2, 3, 5, 7.5, and 10 years. A baseline data set was generated for all systems prior to burial, with these samples being referred to as the Year 0 burst tests. As of the writing of this paper, burst tests were performed for Year 0, 1, 2, and 3.

As mentioned previously, the Year 0 served as the baseline data set for the test program. It was recognized that the due to varying degrees of composite material degradation, these results would be the best that could be expected of all test results. **Figure 5** provides the average hoop strain measurements for the Year 0 75% corrosion samples at the designated pressure levels (72% and 100% SMYS), while **Figure 6** provides actual stress-strain data from two of the burst test samples.

Listed below are the manufacturers participating in the MATR-3-4 program. Shown in parentheses are the lengths of time the respective systems are buried (i.e. either 3 or 10 years).

- Armor Plate, Inc. (10 years)
- Air Logistics Corporation (3 years)
- Clock Spring Company, LLC (3 years)
- Citadel Technologies (10 years)
- EMS Group (10 years)
- Pipe Wrap, LLC (3 years)
- T.D. Williamson, Inc. (10 years)
- Walker Technical Resources Ltd. (3 years)
- Wrap Master (3 years)
- 3X Engineering (3 years)
- Furmanite (3 years)
- Neptune (3 years)
- Pipestream (10 years)

This program has two primary benefits for the pipeline industry. The first is that operators are able to evaluate the available technology and compare the relative performance of competing repair systems. The primary interest concerns the level of strain reduction in the corroded region of the pipe samples, while the pressure at which the test samples fail is also of interest.

A second benefit, and the primary focus of this study, is to evaluate the long-term performance of the composite repair systems. If one considers the 3 and 10 years test periods, the time during which the samples are loaded is approximately 26,300 hours and 87,600 hours, respectively. The 75% corrosion samples represent a relatively severe condition, especially when one considers that 900 cycles at a stress range of 36% SMYS and 4 cycles at 72% SMYS were applied annually to all buried samples.

The results of this program indicate that most of the composite repair systems are able to restore the burst pressure of the externally-corroded pipes to their original condition. The strain gages also demonstrate that even though the strain in the corroded region of the pipe samples are elevated, most are within acceptable levels required for long-term performance. The findings of this program are serving as a critical means for evaluating the long-term performance of composite repair systems and ensuring that those systems evaluated in this study meet the requirements of industry-sponsored standards such as ASME PCC-2 and ISO 24817.

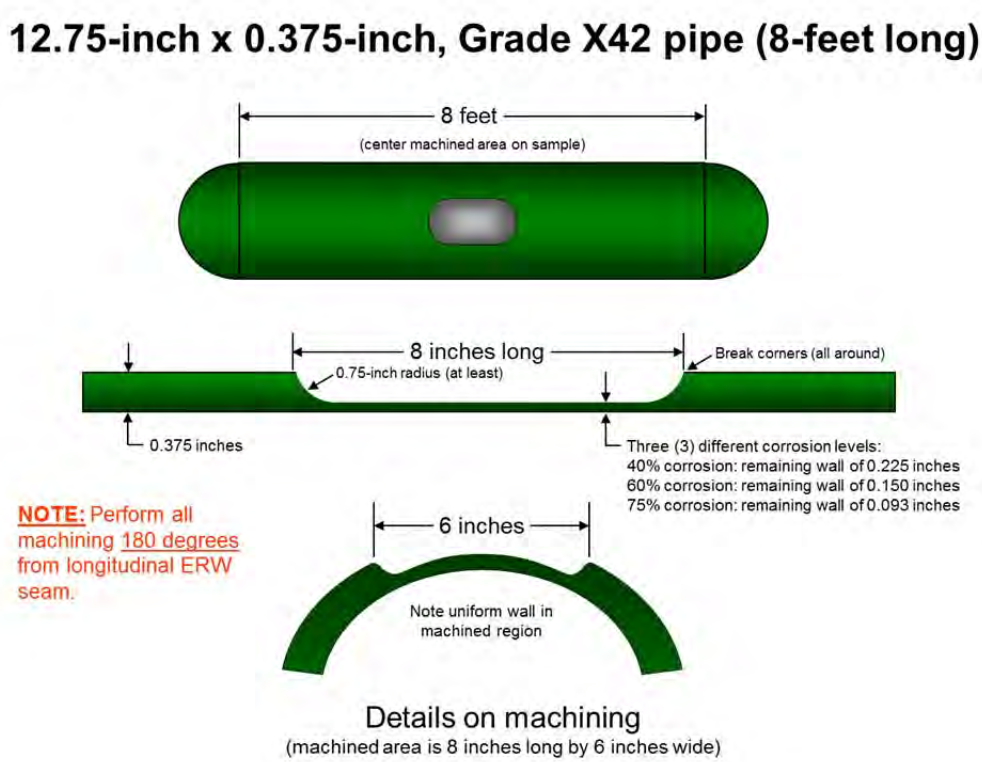

Figure 2: Schematic diagram showing machined corrosion sample

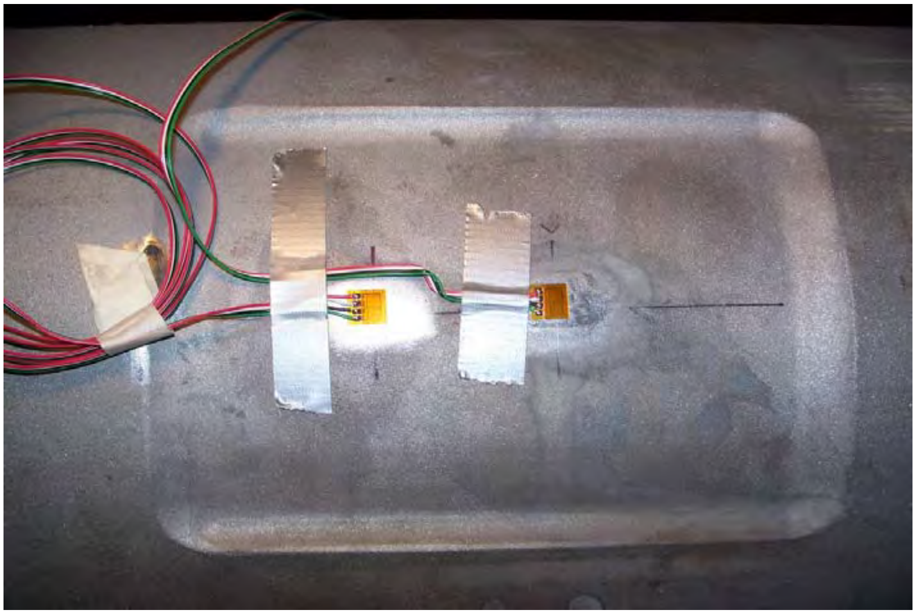

Figure 3: Photograph showing strain gaged in machined region of corrosion sample

Figure 4: Photographs of the MATR-3-4 buried pipeline test facility

ALL MATERIALS	
PRCI average measured strain values for 75% corrosion	
MAOP	3,734 με
SMYS	4,905 με
$MAOP_{min}$	1,828 με
$MAOP_{max}$	8,852 με
$SMYS_{min}$	2,250 με
$SMYS_{max}$	8,791 με
E-Glass Material Only	
PRCI average measured strain values for 75% corrosion	
MAOP	4,497 με
SMYS	5,692 με
$MAOP_{min}$	2,667 με
$MAOP_{max}$	8,852 με
$SMYS_{min}$	3,185 με
$SMYS_{max}$	8,472 με (actually higher, gage failed)
Carbon Material Only	
PRCI average measured strain values for 75% corrosion	
MAOP	2,524 με
SMYS	3,292 με
$MAOP_{min}$	1,828 με
$MAOP_{max}$	3,087 με
$SMYS_{min}$	2,250 με
$SMYS_{max}$	4,106 με

Figure 5: Strain gage measurements from Year 0 burst tests
(Measurements in 75% corrosion samples at 72% and 100% SMYS pressure levels)

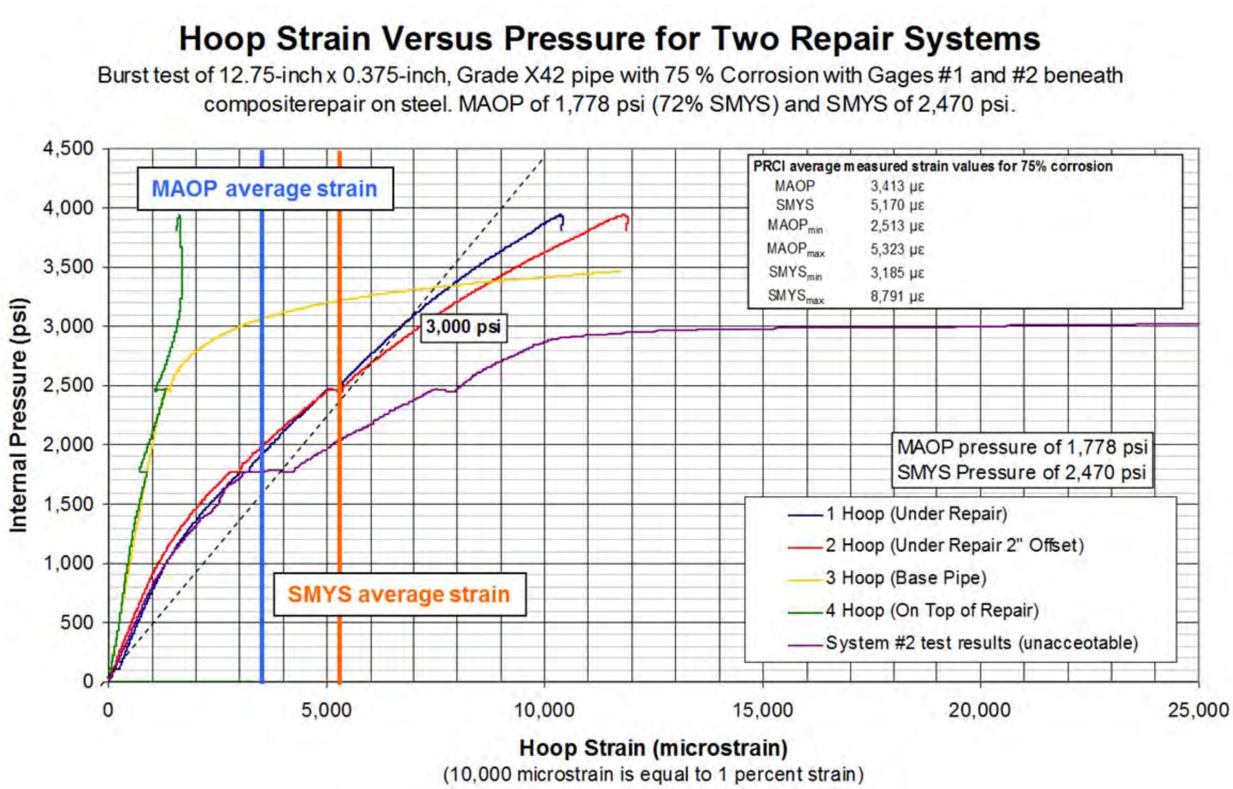

Figure 6: Strain gage measurements from Year 0 burst tests for two competing systems

2.2 MATR-3-5 Dent and Mechanical Damage Study

PRCI funded the MATR-3-5 study, *Composite Repair of Mechanically-Damaged Pipes*, to evaluate the use of composite materials to repair mechanically-damaged pipelines. The purpose of this particular program was to determine if composite materials can effectively repair dents in high pressure pipelines subjected to cyclic pressure service. Much like its predecessor program, MATR-3-4, that is evaluating the long-term performance of composite repair systems in repairing corrosion, this program included the participation of several composite repair manufacturers, and one steel sleeve manufacturer, whose contributions included finances, materials, and personnel time required for installation work.

A total of 11 different repair systems were evaluated in this study, coming from eight composite manufacturers and one steel sleeve manufacturer. These repair systems were used to repair specific dent configurations installed in 12.75-inch x 0.188-inch, Grade X42 pipe ERW material. The dent geometries included plain dents, dents in girth welds, and dents in seam welds. The dents were installed to a depth of 15% of the pipe's outer diameter (1.91 inches) using an NPS 4 end cap as an indenter held in place while the pipe sample was pressurized to 72% SMYS, or 892 psi. A schematic diagram of the 28-ft test samples is shown in **Figure 7**. One test sample of this configuration was made for each of the repair systems, as well as the unrepaired condition. **Figure 8** provides a photo showing one of the installed dents.

After all aspects of the denting process were completed, strain gages were installed on the periphery of the dents (see details in **Figure 7**), after which the repair systems were installed on the outside surface of the pipe, at a pressure of 0 psi. Each manufacturer was responsible for their designs and for performing installations. All repairs included a filler material, also known as the load transfer material, which was used to fill the dented region of the pipe before the reinforcement was installed. In this program, composite fiber materials included E-glass and carbon. One system utilized high-strength steel wound around the circumference of the pipe and bonded with a resin. Matrix resins for the tested systems included two-part epoxies and water-activated urethanes in a pre-impregnated, or pre-cured, form. In this latter case, the binding component in the composite repair system was applied to the cloth and allowed to partially cure. This is sometimes referred to as a "pre-preg."

Each composite repair system was evaluated using a total of six dents, except one system that was only used to repair two plain dents (retest to re-qualify a previously tested system). The six dents in each pipe sample were pressure cycled to failure or 250,000 cycles (whichever occurred first) at a pressure range of approximately 100 psi to 992 psi. These pressure values are referred in this report as having a range equal to 72% of the pressure causing the specified minimum yield strength (SMYS) in the hoop direction, varying from 100 psi, or 8% SMYS to 992 psi, or 80% SMYS. **Figure 9** is a photograph showing a fatigue failure in one of the unrepaired test samples.

Of the 11 tested systems, six products used to repair plain dents were able to achieve the 250,000 cycle run-out condition. The cycles to failure is plotted graphically in **Figure 10**. Some samples ran for more than 250,000 cycles, since the shut-off condition in the cyclic pump was not automated. The results section of this report lists actual cycles accumulated for each sample. One of these systems was cycled beyond the run-out condition to determine the actual limit state of the pipe, which resulted in a fatigue failure of the ERW seam in the base pipe (outside of the repairs) at 358,470 cycles.

Figure 11 includes several important variables of interest in the MATR-3-5 program including the measured strain in the dented pipe beneath the composite reinforcement, number of cycles to failure, repair geometry and material properties, and type of repair. Also included in this figure is composite *stiffness,* defined as the product of elastic modulus and thickness.

The results of this program indicate that when properly designed and installed, composite repair systems are able to restore integrity to mechanically-damaged pipes to a state that makes them fit for continued use at their design conditions. When composite materials are used for repairs, whether the repair involves corrosion, dents, or other anomalies, any integrity assessment should include an estimate of the future history to ensure that the design is adequate for the intended service conditions. This includes the potential for cyclic service.

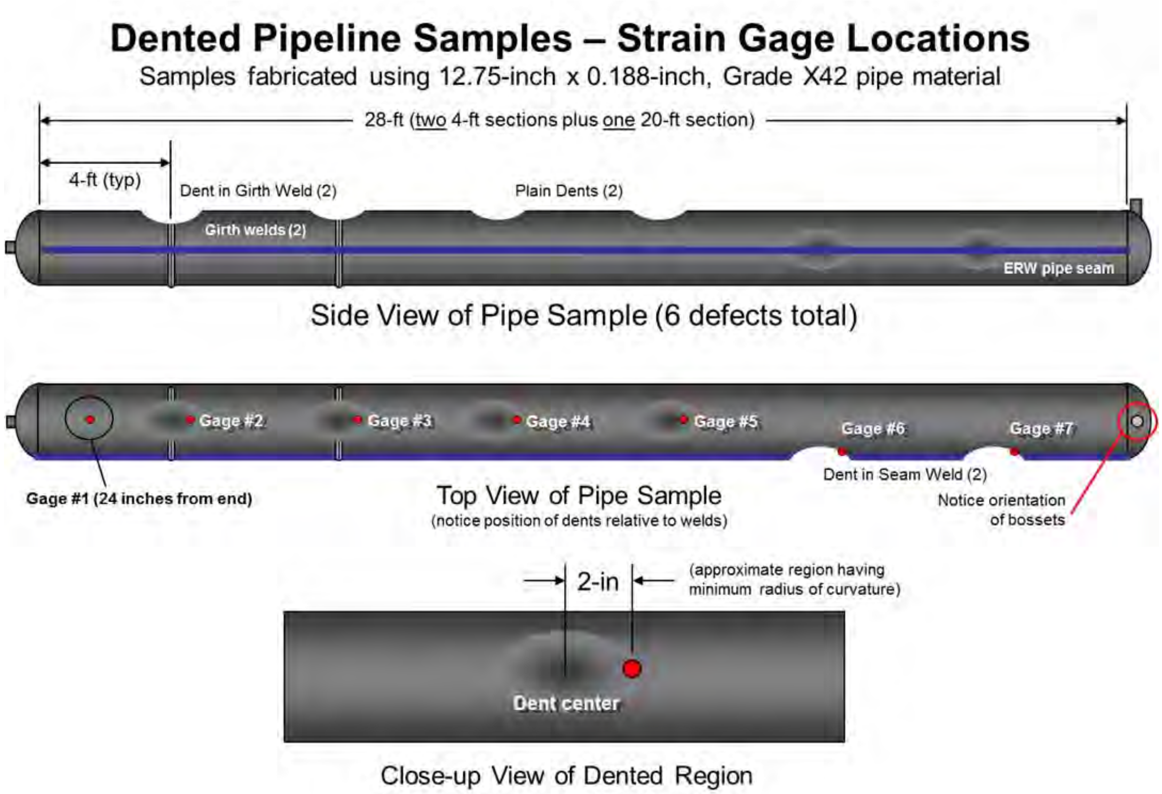

Figure 7: Schematic diagram showing MATR-3-5 dent sample configuration

Figure 8: Photograph showing plain dent test sample after indentation

Figure 9: Photograph showing typical fatigue crack in dented test samples

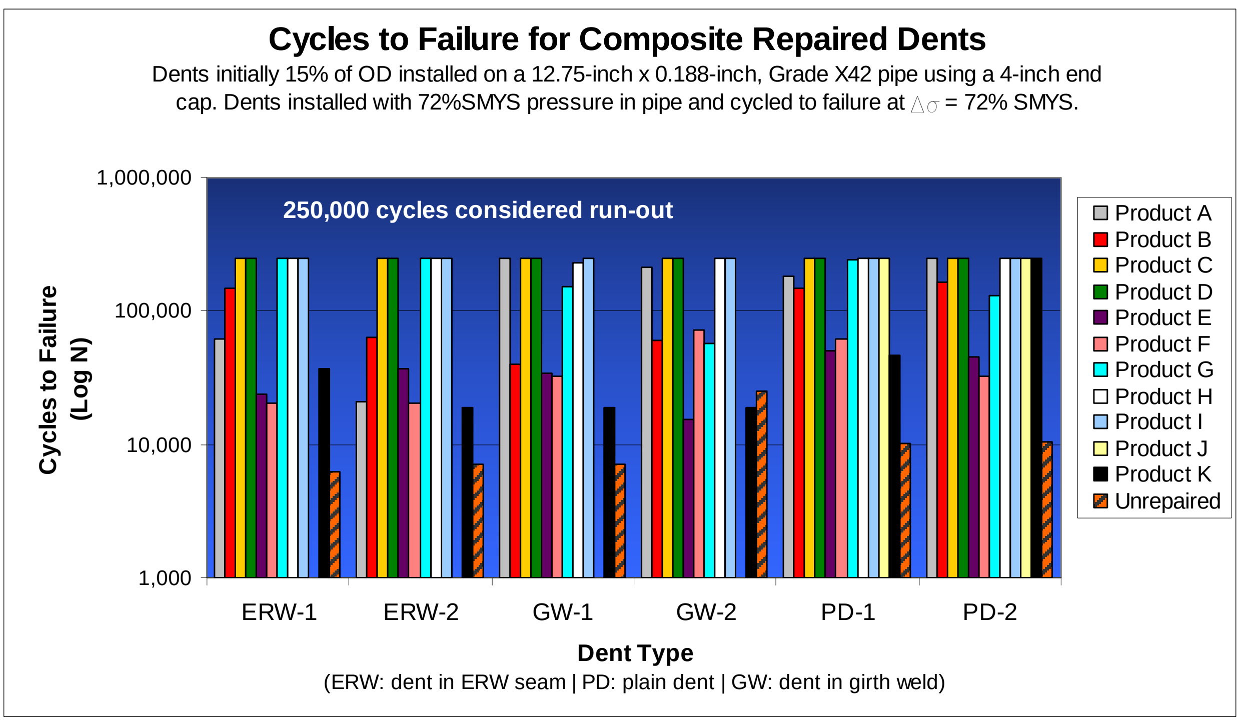

Figure 10: Fatigue test results for composite repaired dent test samples
(Dent configurations: *ERW* is dent in ERW seam, *GW* is dent in girth weld, and *PD* is the plain dent)

Product	# of Cycles to Runout or Failure	Δε (microstrain)	Average Cycles to Failure	Average Composite thickness (in)	Composite Tensile Strength (ksi)	E (psi)	k = E x t (kip/in)	System Type
A	181,857 248,684	1,872	215,271	0.459	56.4	3,000,000	1,376	E-glass Urethane
B	148,892 165,809	1,821	157,351	0.409	72.1	2,000,000	818	E-glass Epoxy
C	305,353 305,353	1,049	250,000	0.658	90.0	4,000,000	2,631	E-glass Coil
D	261,742 261,742	573	250,000	0.439	87.8	7,000,000	3,072	Carbon Epoxy
E	50,334 44,987	2,327	47,661	0.578	52.1	2,630,000	1,520	E-glass Urethane
F	62,324 32,273	1,463	47,299	0.389	70.9	5,480,000	2,132	Carbon Urethane
G	241,864 131,040	960	186,452	0.290	84.4	7,000,000	2,027	Carbon Epoxy
H	358,470 358,446	720	250,000	0.365	70.0	4,400,000	1,607	E-glass Epoxy
I	258,406 258,406	708	250,000	0.202	200.0	30,000,000	6,049	Steel Epoxy
J	426,822 426,822	1,296	250,000	1.281	52.1	2,630,000	3,370	E-glass Urethane
K	46,955 307,438	1,280	177,197	0.375	75.7	30,000,000	11,250	Steel Sleeves
UR	10,163 10,334	3,259	10,249	N/A	N/A	N/A	N/A	Unrepaired

Figure 11: Summary of MATR-3-5 test results including strain gage results

2.3 MATR-3-7 Girth Weld Reinforcement Study

Girth welds are an essential part of every transmission pipeline. With much of the pipeline system in the United States having been installed before 1970, concerns may exist with some pipeline companies regarding the integrity of their vintage girth welds. While it is true that the failure rates in the United States attributed to vintage girth welds (based on information reported to the authorities) have not been widespread, ranging from 2.1% to 8% depending on how the data is interpreted (cf. PRCI Report PR-335-094502, 2010), operators recognize that they cannot be complacent as their infrastructure ages and should continue to look for alternatives to conventional repair and replacement options to ensure integrity.

The MATR-3-7 program, *Evaluating the Use of Composite Materials in Reinforcing Vintage Girth Welds*, was sponsored by PRCI to evaluate the use of composite materials for reinforcing girth welds. Co-participants in this study included five composite repair manufacturers that currently market products and systems for reinforcing pipelines with anomalies and defects. These manufacturers made financial contributions, donated materials, and provided personnel who completed repair installations on their respective test samples. The composite repair manufacturers that participated in this study are listed below:

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

The program involved the reinforcement of 12.75-inch x 0.188-inch, Grade X42 pipe samples that had defective girth welds that did not include a root pass (i.e., simulated lack of penetration weld defects). **Figure 12** provides a schematic of the girth weld configuration, as well as a cross-section showing the lack of penetration in an exemplar weld. **Figure 13** is a schematic diagram showing the MATR-3-7 test sample with strain gage locations.

Each manufacturer was responsible for repairing three pipe samples that included one tension-to-failure sample, one tension-to-failure sample with a reduced bonding area, and a bending-to-failure sample. Additionally, two unreinforced pipe samples with a defective girth weld were tested (i.e., tension-to-failure and bending-to-failure) to provide a baseline data set to which results for the reinforced samples could be compared.

Prior to 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 with 889 cycles per year at a stress range of 36% SMYS. For each test to failure, an internal pressure of 445 psi (36% SMYS) was held constant during testing.

Although there were some differences in the bending capacities for the five sample sets, all of the reinforced systems performed well in the sense that the maximum level of distortion in the pipe occurred outside of the reinforcement. This behavior documented that the reinforced defective girth weld sections of the pipe had greater stiffness than the base pipe itself. However, there were some differences in the results for the tension-to-failure samples. The unreinforced tension sample failed at a tension load of 293 kips, with photographs of the failed samples shown in **Figure 14**.

Considering the reinforced tension samples with full bonding areas, products from Air Logistics, Pipe Wrap, LLC, Citadel, and Armor Plate Pipe Wrap had tension-to-failure loads ranging from 433 to 481 kips. However, the Western Specialties LLC repair was able to achieve a maximum tension load of 522 kips, with a failure occurring outside of the repair in the base pipe near a welded bosset. The load-deflection tension test results for the reinforced and unreinforced girth weld samples are shown in **Figure 15**.

The results of this program demonstrate that when properly designed and installed, composite materials reduce hoop and axial strains in girth welds and increase the limit state capacities under combinations of pressure, tension, and bending loads. Thus, these systems provide operators a repair method that adequately increases the reliability and integrity of pipelines having defective girth welds. The role of high quality surface preparation is essential when discussing axial tension loading; far more critical than when considering the reinforcement of circumferential loading alone.

This program did not specifically address the long-term performance of composite repair systems, although it is recognized that most composite manufacturers in this girth weld study are participating in research efforts to establish the long-term durability/performance of their systems (e.g. PRCI MATR-3-4 program discussed previously). Composite materials are widely recognized as a means for reinforcing damaged pipelines. Programs such as this girth weld study are highly valuable for quantifying the level of performance that can be expected from currently available composite repair technologies.

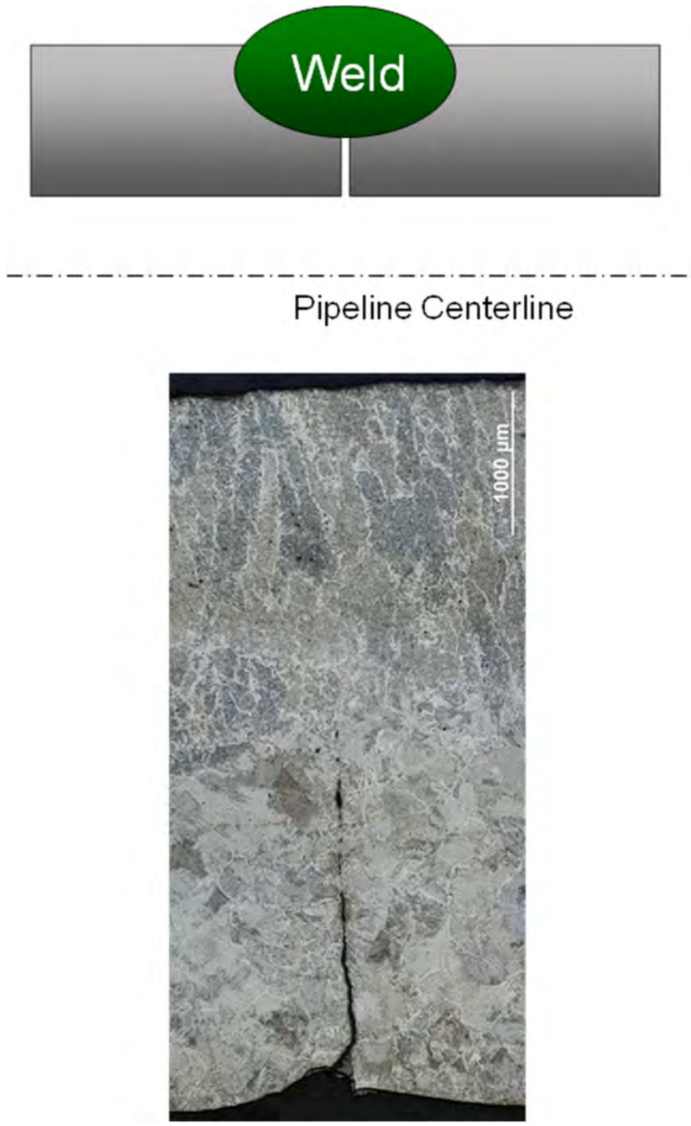

Figure 12: Schematic and photograph showing MATR-3-7 defective girth weld samples

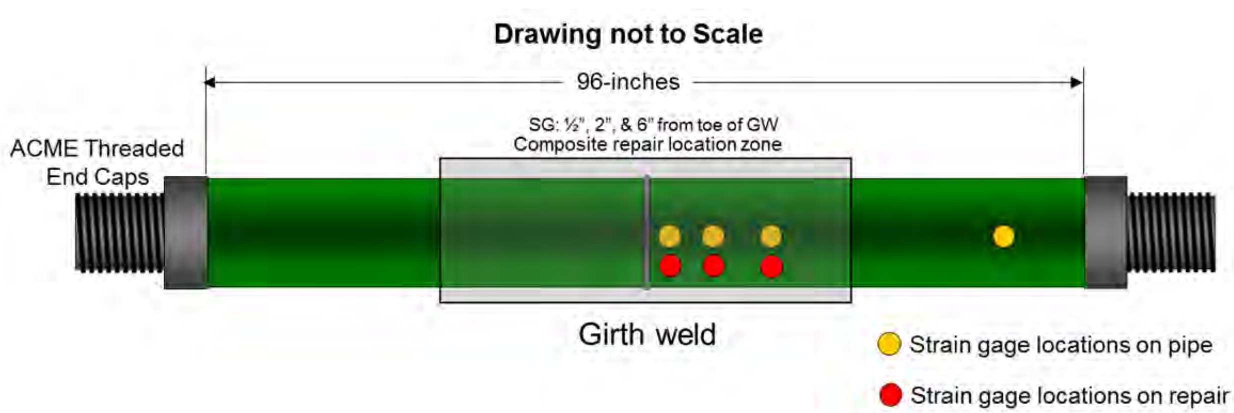

Figure 13: Schematic diagram showing the MATR-3-7 test sample with strain gages

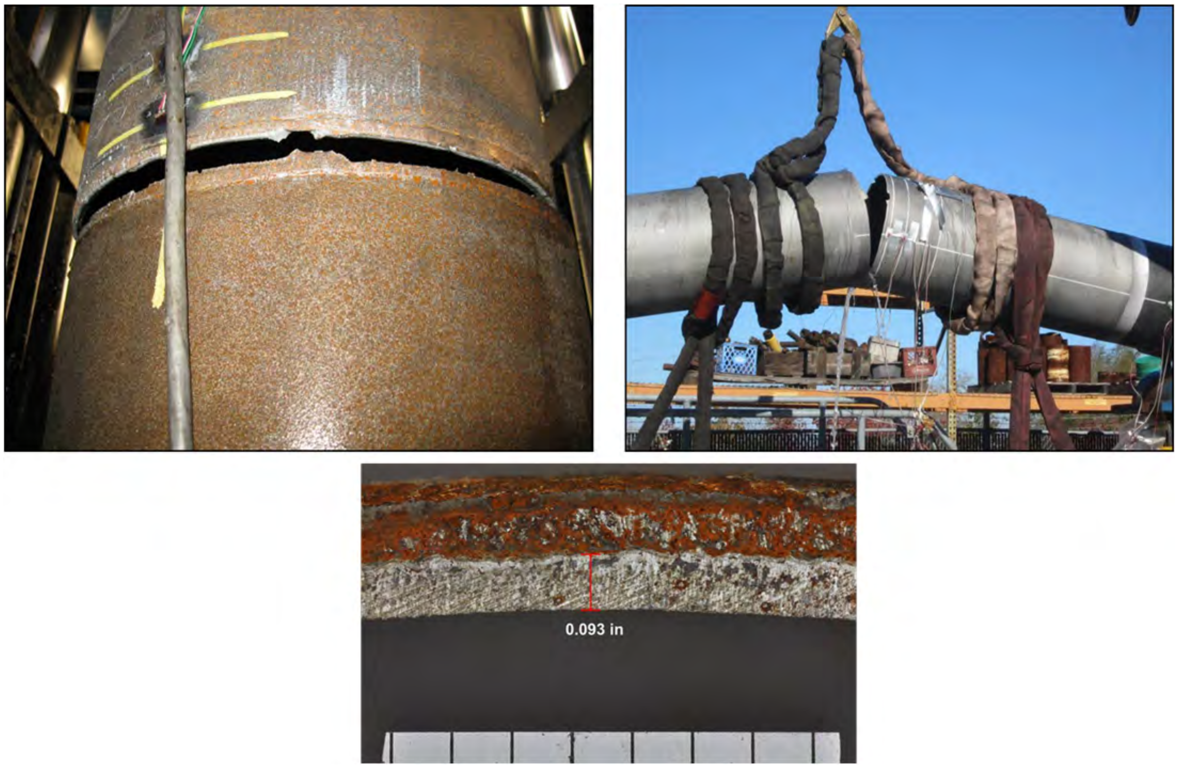

Figure 14: Photograph showing test results for reinforced MATR-3-7 girth weld samples
(Lower image shows a cross-section of the failed girth weld illustrating region with lack of penetration)

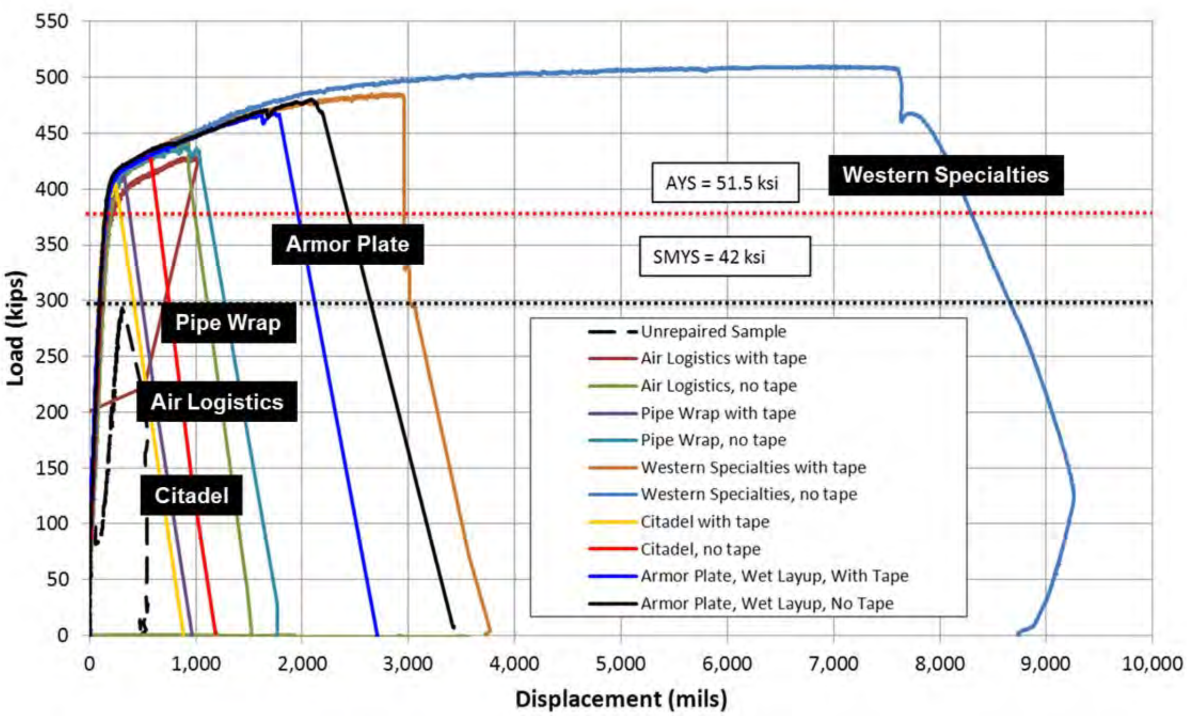

Figure 15: Load-deflection tension test results for the MATR-3-7 girth weld samples

3.0 DISCUSSION

As mentioned previously, one of the key features of the Composite Roadmap is evaluating gaps that exist in composite research. Five areas have been identified for further study and are listed below in order of interest.

1. PRCI Guidance Document for Composite Repairs (Part I: Q/A and Recordkeeping Requirements for Composite Repairs)
2. Effects of Internal Line Pressure During Installation
3. NDE and Effects of Delamination on Performance
4. Elbows and Bends
5. Thermal Expansion

In addition to the above list, other areas of interest identified for further study include the following:

- Surveying pipeline operators to determine their current perspectives on the use of composite materials (including failures)
- Fatigue limits for liquid pipelines subject to cyclic pressures
- Testing program integrating composite repair defects followed by NDE and destructive testing.

Unlike the assessment of steel based on known material properties, evaluating composite repair systems is complicated due to the large number of design variables that exist. As a minimum, these variables include resin type, fiber type, fiber orientation, material thickness, filler (load transfer) material, and installation techniques. Additionally, the time-dependent material properties associated with composite materials add an additional level of complexity to their design and assessment.

Although some success has been achieved in numerically modeling composite repair systems using finite element analysis, the role of full-scale destructive testing in evaluating composite repair systems cannot be overemphasized. Only by destructively testing composite repair systems can industry establish appropriate safety factors for ensuring adequate long-term performance.

4.0 CLOSING COMMENTS

In closing, this paper has provided a brief overview of PRCI's research to date focused on evaluating the use of NMRs in reinforcing and repairing pipelines using the construction of a Composite Roadmap. In building on a strong foundation associated with prior research, PRCI will continue to support the pipeline industry in funding research programs to expand the safe use of quality composite repair systems. These efforts are focused on ensuring the long-term integrity of gas and liquid transmission pipelines by properly designing composite repair systems to reinforce anomalies as they are identified.

The results of the PRCI programs presented in this paper, as well as other research efforts such as those sponsored by composite manufacturers and other organizations, are critical for evaluating the long-term performance of composite repair systems in repairing a range of pipeline anomalies. Equally important, programs such as this these influence the direction of consensus standards such as ASME PCC-2 and ISO 24817 to ensure that composite systems can properly repair a wide range of pipeline anomalies.

5.0 ACKNOWLEDGEMENTS

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